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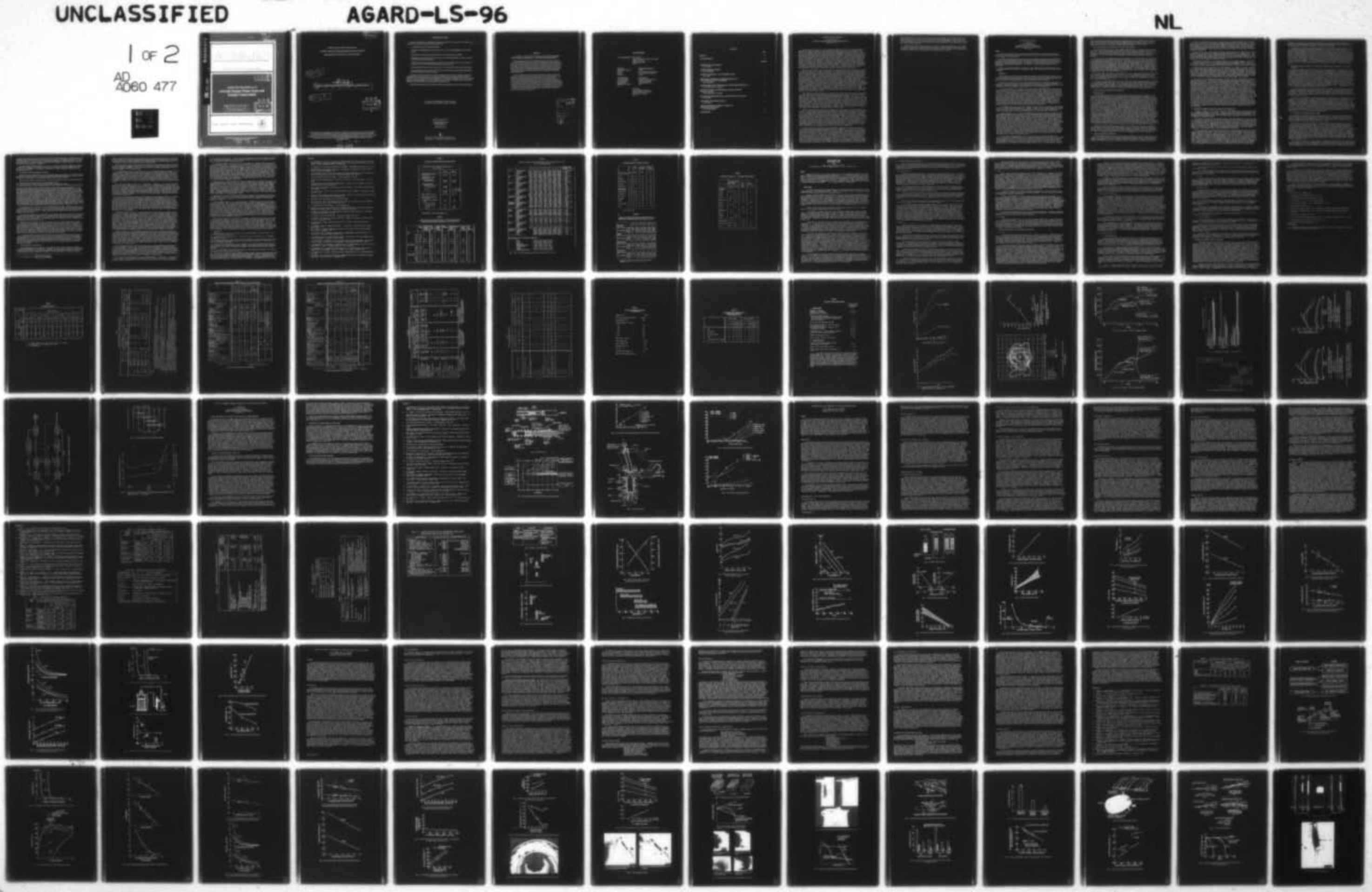

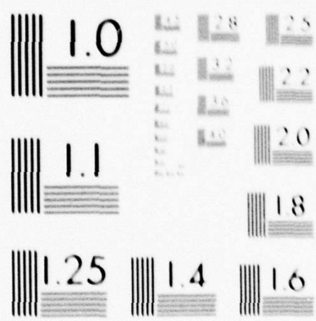

MICROCOPY RESOLUTION TEST CHART

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Aircraft Engine Future Fuels and Energy Conservation

NORTH ATLANTIC TREATY ORGANIZATION

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PREFACE

This AGARD Lecture Series No. 96 is sponsored by the Propulsion and Energetics Panel of AGARD and is implemented by the Consultant and Exchange Programme.

Future fuel supplies for aviation is an important matter. If the world continues to consume its petroleum resources at its current rate of consumption, it will essentially run out of these resources by the turn of the century. The need for aircraft fuel conservation is most urgent, if not mandatory, because the future of aviation as we know it today, is at stake. This lecture series is designed to provide various interested members of NATO with a better understanding of the problems facing the aerospace community and to provide an opportunity to review and assess what steps can and are being taken to alleviate this international problem.

Current and forecasted world energy demands, growth, and supply are reviewed in perspective to the status and outlook for future aviation fuels to meet NATO needs. The special problems associated with the refining of aviation fuels from lower quality feedstocks (including fuel refined from coal, oil shale, and tar sands) and techniques for reducing energy consumption in refining processes are examined. Special attention is given to the chemistry and combustion characteristics of future hydrocarbon fuels and the impact of using these fuels in aircraft engines and fuel systems. An assessment is made as to what technology advancements are currently underway and what other advancements are needed with reference to engine components, engine systems, aircraft designs and operational procedures to help conserve fuel resources.

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INTRODUCTION AND OVERVIEW

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For many years most of us in the aviation community felt that the conservation of hydrocarbon fuels was someone else's problem not ours; after all, the automobile and industry in general were the prime users of petroleum-based fuels, not aircraft. But now, we are rapidly approaching the day where the automobile manufacturers and industrial communities will have done practically everything possible to conserve energy and we in the aviation community will be asked what we have done to alleviate the energy problem. From the statistics point of view we are now in a period of time that some consider as a time of "plenty" and which might last to about the close of this century. We now no longer measure our oil resources in terms of centuries, but recognize that a time of "famine" is rapidly approaching. Simply put, our demand for fuel is outstretching our ability to supply fuel. Therefore, it appears that now is the time to take some appropriate actions and to profit from the early scriptures by making full use of this time of "plenty" to prepare for the "famine" of the future. Although none of our lecturers profess to be like the prophets of old, I think you will agree with me that their epistles make a great deal of sense and offer us some hope for the future.

The need for aircraft fuel conservation is extremely important, because the future of aviation as we know it today is at stake. We also know that fuel conservation alone will not be sufficient to maintain adequate fuel resources for aviation, particularly in view of predicted aviation growth rates and the probable future petroleum supply situation, not just in regard to quantities and economics, but also in regard to the nature of the crude oil itself. As our lecturers will point out, the general availability of previously abundant high-grade crudes is decreasing and will probably continue to decrease as our search for oil expands to all corners of the earth. The lower grade crudes, usually degraded by large concentrations of aromatic hydrocarbon components, will have the effect of reducing the fraction of the barrel (middle distillates) which is naturally suited for jet fuels and which requires minimum processing to meet current fuel specifications. The demand by other users in the energy marketplace for these middle distillates are also expected to increase in the future, further threatening the jet fuel supply availability for aviation use. Therefore, in addition to fuel conservation, other measures must be sought to assure a reasonable fuel supply for aviation use. These other measures include the use of alternative fuel sources and the creation of a broader specification for jet aviation fuels.

The feasibility and practicality of possible jet fuels other than current specification type hydrocarbon fuels has been studied by many investigators. Methanol, methane, hydrogen, and a range of kerosene-type hydrocarbons made from shale oil, coal, or tar sands are some of the candidate alternate fuels that were studied. The studies indicated that methanol, methane and hydrogen were not realistic or near-term solutions to the jet fuels problem, although hydrogen was noted as particularly attractive for very long-term potentials, beyond this century. The alternative fuels refined from shale oil, coal, and tar sands appear to have the most potential in terms of availability for future energy users including aviation, since these fuel feedstocks are relatively plentiful and can be made available in the near-term time period. These fuels, if they can be economically produced without seriously impacting the environment, afford an opportunity to relieve the present total dependence on petroleum as a fuel source.

These alternative fuels must also be compatible with present aircraft systems and be able to be used without degrading performance or other desirable operational characteristics. To make these alternative future jet fuels economically acceptable, a broader or more permissive fuel specification than present ones will be required particularly a specification which can permit an optimal compromise between fuel refining requirements and engine and fuel system compatibility requirements. More on this subject will be discussed by the other lecturers. It is very important to recognize that minimizing total fuel and energy costs for future aircraft will necessitate trades among refinery energy and costs, aircraft fuel costs, and total energy conservation. The adaptation of a broadened fuel specification to current petroleum fuels will relax the growing pinch on petroleum based fuel availability by increasing the fraction of the barrel which can be used economically for jet fuels, and help provide the user with some relief, at least until alternative fuel sources come on line in significant quantities.

During this Lecture Series, we will attempt to provide you with a better understanding of the energy problems facing the aviation community. Current and forecasted world energy demands, growth, and supply will be reviewed in perspective to the status and outlook for future aviation fuels to meet NATO needs. The special problems associated with the refining of fuels from lower quality feedstocks (including fuels refined from coal, oil shale, and tar sands) and techniques for reducing energy consumption in refining processes will be examined. The chemistry and combustion characteristics of future hydrocarbon fuels and the impact of using these fuels in aircraft engines and aircraft fuel systems will receive special attention. Finally, an assessment will be made as to what technological advancements are currently underway and what other advancements are needed with reference to engine components, engine systems, aircraft designs and operational procedures to help conserve aircraft fuel resources and alleviate this

international problem. The Lecture Series will be concluded with an *Open Forum Round Table Discussion*, at which time, the lecturers, host country guest speakers, and the general audience will have an opportunity to review the highlights of the Lecture Series and discuss issues and concerns that may have been overlooked or not adequately covered during the formal lectures.

In the short time we have for the Lecture Series, the presentations, by necessity, are somewhat limited in scope and depth. However, I believe you will be able to find sufficient references in the lecture notes to enable you to obtain a more comprehensive in-depth treatment of the subject matter discussed in the lectures.

FUTURE FUELS FOR AVIATION

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SUMMARY

The historical background of the current aviation gas turbine fuel specification is described. Current local supply difficulties are discussed in relation to crude oil availability and the pattern of regional demand for petroleum products.

The consensus of expert opinion on the effects of predicted future petroleum resource availability and of various trade and economic factors on future rates of production are described. Recent data on the demand for petroleum products and the crucial importance of future demand control are discussed. The prospects for petroleum based aviation fuel are evaluated. The long term sources of aviation fuel are described and the problem areas enumerated. The need for a research program on alternative fuels is demonstrated.

Previous work using model flames on the effects of fuel composition on rich flame chemistry is reviewed and the potential contribution of fundamental research in the alternative aviation fuels program is outlined.

1. INTRODUCTION

The motivation for this lecture derives from active concern in the United States of America to secure, for the medium and long term, specifications which will describe fuels for aero gas turbines engines which can be derived more economically and in sufficient quantity from more restricted fossil fuel resources and which will continue to permit satisfactory engine and aircraft operation.

An increase in research activity in this area, largely under N.A.S.A. sponsorship, was brought to the author's attention (at that time, Head of Combustion and Instrumentation Technology Department at the National Gas Turbine Establishment) in the Autumn of 1976, by various United Kingdom visitors to the U.S.A. from Ministry of Defence (Procurement Executive) {MOD (PE)} and from Rolls-Royce Ltd.

At that time, relaxations to the present Jet A_1 specification (DERD 2494, AVTUR 50) were being canvassed, particularly with regard to aromatics content and freezing point temperatures, to relieve shortages which were said to be occurring on the U.S. west coast due to reduced availability of suitable types of crude oil. These relaxations could be expected to do little however to relieve the more severe shortfall in jet fuel which was predicted for the medium to long term if expected increases in U.S. demand and decreases in crude oil supplies were realized. The pattern of U.S. demand for refined products was such that any significant increase in the fraction of crude oil being used for jet fuel must imply the inclusion of material from the diesel fuel range. The possibility that the resultant deterioration in low temperature properties might need to be alleviated by the inclusion of some gasoline fraction caused particular concern in the U.K. since it raised important issues of aircraft fuel safety. Indeed, the U.K. was active in fuel additive research, aimed at eliminating even the more restricted fuel safety problems experienced with aviation kerosene - particularly those under aircraft crash conditions. The inclusion of gasoline in the fuel would nullify the effects of such additives.

It was realized that the U.K. aero engine industry would have to pay close attention to these developments if it wished to remain competitive in U.S. markets. Further, while it could be argued that European aviation fuel supplies were less likely to be constrained in this way in the short to medium term (5 to 10 years) the problem was likely to be encountered there also in the longer term (10 to 20 years).

In order to establish a U.K. view of the problems which might arise, a working party under the chairmanship of the author was convened in March, 1977, comprising representatives of the airframe and engine sides of MOD (PE) and of the U.K. aero engine industry. A working paper, discussing the problem and its implications and outlining a possible program of work required, was presented and discussed at a meeting of the MOD (PE) Turbine Fuels Committee on the 27th April, 1977. The text of this paper, updated in the light of comments received from members of the committee is being published (1). The reaction of this committee to the paper was polarized, predictably enough, between the petroleum industry representatives, anxious as always to obtain any relaxation of the fuel specification which would ease their supply problem and the user side, covering both airframe and engine industry representatives anxious, if possible, to maintain the status quo. In particular, after referring to the potentially high cost of programmes of empirical engine development to cope with higher boiling range, high carbon/hydrogen ratio fuels, the users wanted to know what was the likely extra cost of the alternative approach - of making increased amounts of fuel to the present Jet A_1 specification by means of established refining techniques of conversion and by hydrogenation. One oil company representative produced, on the spot, a ball park figure of a 5% increase in fuel costs. Subsequent to the above meeting, the N.A.S.A. sponsored activities have been discussed in detail in several publications (2.3 for example) which have broadly confirmed the word-of-mouth details on which these discussions were based.

It is evidently of some importance to N.A.T.O. that the correct choice should be made on how, collectively, the various member countries in the organization should proceed in this matter. The present paper can probably best serve this end by making a detailed re-examination of the premises on which the various arguments are based. This will cover (1) the consensus opinion on the future availability of petroleum crude, (2) the pattern of demand for petroleum products prior to and since the 1973 crisis in petroleum supply, (3) the constraints placed on member countries by their individual patterns of demand,

(4) the likely long term methods of aviation fuel production and thence, the most advisable interim procedure. While wishing to avoid encroaching on the areas covered by later speakers in the team, the writer's past experience in certain basic areas of combustion research will be called upon, briefly, to demonstrate the constraints of combustion chemistry and fluid dynamics on choice of fuel.

2. HISTORICAL BACKGROUND OF THE PRESENT AVIATION FUEL SPECIFICATIONS

The first Whittle gas turbine (4) used a combustor design based on the industrial furnace practise then current. With increased operational safety in mind, the fuel chosen by Whittle for these first tests was gas oil. When failure of the first combustor design led to experiments with designs using fuel vapourizer tubes within the primary flame, a fuel with a somewhat lower boiling range - kerosine - was substituted. This fuel was retained for the subsequent successful combustion system using pressure atomizers.

For safety in home use, domestic kerosines have flash points above 100°F (37.8°C) and the marketing practise has grown up of dual branding for domestic and aviation use. A specification for aviation kerosine - DERD 2482 (AVTUR, Jet A) was issued in 1951. Two important limits in this specification were a maximum freezing point temperature of -40°C and the control of carbon/hydrogen ratio by limiting the aromatic hydrocarbon content to 20% maximum, there being then no suitable method in use in the refinery laboratories for the direct measurement of carbon and hydrogen content of the fuel. Subsequent experience of minimum aircraft fuel tank temperatures significantly below -40°C in long flights at high altitude in certain combinations of destination, season and weather conditions, led to the introduction of a -50°C freezing point kerosine (DERD 2494, AVTUR 50, Jet A_1) in March 1957. The 20% aromatics limit was retained. The lowering of freezing point was accompanied by a noteable reduction in final boiling point temperature from about 280°C for Jet A to around 250°C for Jet A_1.

To maintain common specifications, Working Party 15 of the Air Standardization Coordination Committee, covering aviation fuels, lubricants and allied products was set up, with regular meetings of delegates from U.S.A., Canada, New Zealand, Australia and U.K. Later, a similar N.A.T.O. body was set up, the N.A.T.O. Military Agency for standardization - Aviation Fuels and Lubricants Working Party, with representatives from all member nations.

To cater for increased fuel availability in the event of war, a specification for a wide boiling range fuel was agreed (DERD 2486, AVTAG, JP4). This had no lower limit on flash point temperature (putting it in the same category as gasoline under British law from the point of view of safety in handling), raised the maximum permitted aromatics content to 25% and lowered freezing point to -58°C. While all military aircraft have to be cleared for operation on both fuels, regular routine use of the wide-cut fuel is limited to the U.S. forces, other N.A.T.O. air forces and nearly all civil flying being based on Jet A_1.

3. CRUDE OIL RESOURCES, PRODUCTION AND CONSUMPTION

3.1 Sources of data

For the twenty-five years prior to the 1973 petroleum crisis, the most widely available, detailed summary of fuel and energy statistics is undoubtedly the United Nations Statistical Yearbook (5). One difficulty with this publication is that the volume dated for a particular year only becomes available towards the end of the succeeding year and then only contains data up to the year prior to the nominal date year. This leaves a gap of 2 to 3 years which, while it is not important when looking back over periods of ten to twenty years of steady progression, is not adequate for rapidly changing situations such as the one which we have experienced since 1973. This does remain the only publication covering statistics for all members of N.A.T.O. The nine member countries who are also members of the E.E.C. are covered by the Eurostat publications (6), which originally appeared quarterly and have more recently been published monthly with data three months in arrears and with separate series of bulletins for hydrocarbons and for solid fuels. The United States fuel scene used to be covered mainly by various commercial publications but the Federal Energy Agency now also publishes a monthly bulletin of statistics (7) with data three months in arrears. One problem with this latter is that, unlike the others (5, 6) which give data in metric tonnes, the F.E.A. data is volumetric, the unit of volume being the United States Barrel. The density changes (and apparent volume growth), which occur during normal refining to the wide range of products now available, make the data difficult to handle. The help of the Energy Attache, at the United States Embassy in London, in overcoming this difficulty is gratefully acknowledged. Having evidently met with the same problem himself, he had sought out and was able to pass on values of factors converting U.S. Barrels to metric tonnes for a world average crude oil and for average specimens of the four main types of major refined products - Motor Gasoline, Jet Fuel, Distillate Fuel Oil and Residual Fuel Oil. These factors came originally from the Statistics Division of the British Petroleum Company, whose help is also gratefully acknowledged, particularly for access to a copy of their 1976 Statistical Review of the World Oil Industry (8). This review has been issued privately, annually since 1956, with data some 6 months in arrears.

Comparisons have been made between annual values of total yearly energy consumption derived from detailed figures for the various fossil fuel categories in (6, 7) and values for the same total given in the most recent U.N. statistical year book (1976) and agreement is very good. Where direct comparison is possible, values in (8) are significantly higher than corresponding values in (6, 7) (e.g. up to +10% on U.S. Natural Gas Consumption data and +10 to +13% on U.S. consumption of total petroleum products.

3.2 Crude oil resources and production

During the twenty years prior to 1973, the world total consumption of crude oil increased at a fairly steady rate of +7% per year, that is, effectively doubling every ten years. The discovery of fresh oil reserves, although more erratic, also showed this average rate of increase so that, for this period, the apparent life index (the ratio of proven resources to rate of production) was steady at about 30 years.

A N.A.T.O. Long Term Scientific Study on military fuels was concluded in January, 1975, in the wake of the 1973/74 oil crisis and its findings were hampered by the fact that the future behaviour of oil demand, because of the effects of the major price change which had just occurred, was quite unpredictable. Future demand level could be affected by adverse trade and by monetary policies. While future supplies could be affected by possible conservation of resources by oil exporting countries by means of restriction of resource development, a major uncertainty was the actual ultimate size of the total economically recoverable resources (U).

Parent and Linden (9) in their empirical projection, used a resource base of 3000 x 10^9 U.S. Barrels, deriving this from a summary report of the National Petroleum Council (U.S.A.) in December 1972. Using an empirical equation, based on the assumption that annual rate of discovery of new resources will continue to grow exponentially, subject to the constraint of the fraction of ultimately recoverable oil yet to be discovered, they deduced that reserves would reach a maximum by 1990 and that life index would then decrease to a level of 12 years by the end of the century.

To demonstrate the effect of U, a second set of projections was produced, based on U = 4000 x 10^9 U.S. Barrels which showed that the date of maximum reserves was only postponed by about 5 years and the life index by a similar increase. This treatment expected world energy demand to go on increasing at 5 to 6% per year and that crude oil demand would increase faster than this until met by resource limitations.

Probably the most authoritative more recent pronouncement on this subject is the report of the Workshop on Alternative Energy Strategies (W.A.E.S.) (10). This gives the consensus opinion of a team of thirty experts from fifteen industrialized countries, meeting at regular intervals over a period of more than two years. This suggests that 2000 x 10^9 U.S. Barrels is the figure for U towards which geological opinion is now converging, a figure which includes reserves in the communist countries. The report admits a range of possible values of U from 1600 x 10^9 to 3000 x 10^9 and using a somewhat controversial figure of 20% for percentage of reserves in the communist area, studies the effects of three levels of reserves for W.O.C.A. (the World outside the communist area) of 1300, 1600 and 2400 x 10^9 U.S. Barrels.

On tne basis that it is impossible to produce at an annual rate of more than 10% of the primary recoverable reserves without reducing the total amount eventually recovered, the minimum feasible life index is placed at 10 to 1. Since different oil discoveries are concurrently at different stages of their development, an aggregate figure of 15 to 1 for minimum life index is assumed. For 1975, the W.O.C.A. cumulative production is 291 x 10^9 U.S. Barrels and the remaining proven reserves 555 x 10^9 U.S. Barrels. Two future rates of addition to reserves of oil are considered:- (a) 20 x 10^9 U.S. Barrels per year which is coupled with high rates of economic growth and rising prices and (b) 10 x 10^9 U.S. Barrels per year, coupled with low rates of economic growth and substantially constant prices. The effects of the different variables are summarized in Table 1. On the basis of a preferred value of U for W.O.C.A. of 1600 x 10^9 U.S. Barrels, it is shown that for case (a) above, with no artificial limitation of rate of production, the latter would peak at some 86 x 10^6 Barrels per day in 1997. With production limited by O.P.E.C., the curve peaks at 71 x 10^6 Barrels per day in 1988 for a production limit of 45 x 10^6 Barrels per day and at 56 x 10^6 Barrels per day in 1981 for a production limit of 33 x 10^6 Barrels per day. The values for case (b) above are:- with no production limitation, a peak of 66 x 10^6 Barrels per day in 1993, at 61 x 10^6 Barrels per day in 1989 for an O.P.E.C. production limit of 40 x 10^6 Barrels per day and at 51 x 10^6 Barrels per day in 1983 for an O.P.E.C. production limit of 33 x 10^6 Barrels per day. The effects of these artificial limitations of production by O.P.E.C. would be to slow down the decline in oil supplies so that total production would remain above the 1975 level until 2027 AD for case (a) and 2013 AD for case (b). Finally, it is argued that if U for W.O.C.A. proves to be higher than the figure of 1600 x 10^9 U.S. Barrels used for the above calculation, the effect would be more likely to extend the oil availability plateau into the 21st century rather than to increase oil production substantially before 2000 AD.

3.3 The pattern of demand for petroleum products before and since 1973

The figure of 7% per year for the rate of increase in world demand for oil in the two decades before 1973 is somewhat misleading. The situation is analysed in Table 2 which summarises consumption of total energy and of the major types of fossil fuels - petroleum, natural gas and coal during this period for the whole world, for North America and for Western Europe (due to an accident of data availability, the two decades used overlap by one year).

The latter both had similar steady rates of increase in total energy demand of just over 3% per year for the whole period, compared with a value of 4.6% for the whole world. When this is broken down into fuel types however, there are significant differences between the two regions. North America had a steady rate of increase in demand for petroleum similar to the rate for total energy (+3.7% per year), with a much slower increase in coal consumption and with an initially high rate of increase in natural gas consumption, slowing down in the second decade. By contrast, Western Europe was in a period of considerable change, with a large rate of increase in petroleum consumption, slowing down in the second decade, a falling rate of coal consumption and a rapidly expanding use of natural gas.

The major influence for change in the period following 1973 was a very rapid increase in the price of crude oil to between three and four times its pre-1973 cost. A detailed summary of the effects of this change on energy use in the E.E.C. countries and in the U.S.A. is shown in Table 3. For all of these countries, there is a predictable reaction away from petroleum fuels, the data for 1974 and through 1975 showing a substantial decrease in petroleum consumption - 7% per year for the E.E.C. group and -3.3% per year for the U.S.A. In 1976, with the notable exception of the U.K., there is a general swing upwards, +8% for DBR and +7% for France and Italy among the major users. The U.S.A. figures show +8.8%. The U.K. shows a further decrease of -1½%. It was tempting to expect this general rise to herald a return to the historic, pre-1973 increment of +7% per year but the 1977 data soon dispelled this with the aggregate E.E.C. figure decreasing by 3%. For 1977, the U.S.A. showed a continuing increase of +6.4%. Table 3 also lists consumption of natural gas, hard coal and other energy sources (electricity generation by

geothermal, hydro-electric and nuclear power installations) all in terms of millions of tonnes of oil equivalent. In calculating the oil equivalent of these other energy sources, a generating efficiency of 35% was assumed for the supposed, substitute, oil-fired steam based system.

The behaviour of the total energy consumption figures over this period is much less dramatic. Most of the individual countries show an overall incremental rate for total energy consumption of +1 to +1½% per year, with a quite general small dip below this rising characteristic for 1975. The decrease in European petroleum consumption has been replaced, largely by natural gas which, for the E.E.C. as a whole, shows an increment, averaged over the period, of +6.8%. The additional factors in the U.K. have been the availability of coal and the fact that many of the thermal power stations were designed to operate satisfactorily, alternatively either on coal or on residual fuel oil. The sharp increase in coal consumption in 1975 reflects a return from oil firing to coal firing, as a matter of central policy, in many of these power stations. The other major coal producing country in Europe - West Germany - has shown a continuing decline in hard coal consumption (-2.6% per year for the period) while the production of brown coal (not included in the Table 3 Summary) is also decreasing rapidly (-8.6% for 1977). There have been recent reports of increased investment in West German coal mining however which should, in time, reverse these trends.

3.4 *Constraints imposed by differences in the pattern of demand for petroleum products in individual countries*

Attention has already been drawn in the previous section to differences in the make-up of the total energy package and differences in trends for individual fuels between the E.E.C. countries and the U.S.A., as evidenced by the data in Table 3. A further constraint is applied by the very substantial differences in the pattern of consumer demand for refined products. These differences are shown in Table 4 which gives a detailed breakdown of refinery products for the year 1975 for the whole world, for the United States of America, for the world other than the U.S.A. and for N.A.T.O. countries without the U.S.A. It should be noted that the 1975 figure for weight of total products given in column 2 of Table 4 is substantially smaller than the 1975 total products consumption figure in Table 3. The value in Table 4 is for petroleum products actually refined in the U.S.A. The difference between the two totals reflects the very substantial trade in imports of finished products in the U.S.A. The magnitude of trade, not only in crude oil but in imports and exports of finished products to and from individual countries, is such that data expressed solely as production figures can give a misleading impression. For this reason, Table 3 is given in terms of product consumption although this ignores the few percent of crude oil represented by refinery losses. These losses are expected normally not to exceed 5%.

If we turn now to Table 4, the last two columns show the breakdown of products typical of refineries in Europe and the Middle East, with gasoline at 16 to 18% and a total kerosine fraction of about 7% which is marketed in different ways following the pattern of local demand. Distillate fuel oil (including diesel fuels) is about 25% and some 40% is used as residual fuel oil, the bulk of which will be burned in boiler furnaces. The very small amounts of petroleum coke produced (about 0.2%) indicates the very limited use make of thermal cracking.

In the U.S.A. on the other hand, something approaching 70% of the crude oil is used as fuel for transportation of one form or another. Various conversion techniques are used to maximise gasoline yield - the production of coke approaching 4% suggests the extensive use of thermal cracking. Distillate fuel oil production is at a similar level to European practise but residual fuel oil is only just over 11%. The U.S. pattern of product demand is still developing and changes in demand for the four major product types for the period 1972 to 1977 are shown in Table 5. Gasoline demand shows an average annual rate of increase of +2.4% and thus represents a decreasing fraction of the total crude (42.9% for 1977 as compared with 48% in 1972). Jet fuel shows a similar average annual increment (+2.8%) and again, as a percentage on crude, the yield has decreased, from 7% to 6.4%. Distillate fuel oil shows only small annual fluctuations. The major change has been in Residual fuel oil production, which have very nearly doubled over this short period. Residual fuel oil is also the largest imported finished product.

4. THE PROSPECTS FOR CONTROLLING CRUDE OIL DEMAND

The absolute availability of petroleum crude to meet at least the current rates of total products demand would seem to be reasonably assured until the year 2025 or so. The W.A.E.S. predictions (14) on which this optimistic-looking statement rests are based on a fairly conservative view of ultimate total crude oil resources and it is also assumed that O.P.E.C. will take steps to limit production (such a proposal was reported in the London Financial Times in May, 1978).

The question of future levels of demand for petroleum products, which, evidently, must qualify this crude oil availability, requires some diplomacy in its discussion since there appear to be two quite different sets of requirements within N.A.T.O. The E.E.C. countries have reduced their aggregate crude oil intake by some 50 million tonnes per annum since 1973 and it is difficult to detect any positive further trend in demand over the past three years. Since a major fraction (40%) of the E.E.C. crude oil intake has been used in the past as Residual fuel oil, central government policy can fairly readily control future demand for this product, for which there are alternative energy sources available - imported coal, nuclear power and natural gas. The price mechanism will tend to reinforce this trend. These comments apply to about one half of the N.A.T.O. total crude oil intake. There has also been plenty of evidence, reported in the press, of major new investment in European refineries in new cracking plant. This suggests that the oil companies expect the down turn in Residual fuel oil demand to be permanent, thus releasing feedstock for conversion to lower boiling range premium products. This would tend to further reduce the pressure of demand for crude.

The situation in the U.S.A. is rather different. The fact that the major part of the crude is refined to produce fuels for piston engined transport means that demand for these is not so easily susceptible to central government control. Due, in some measure, to a long standing cheap fuel policy (whereas European gasoline has always had an increasingly high fiscal burden to carry) the U.S. automobile has developed to

a typical engine capacity some four times as great as that of most European cars. European gasoline consumption per mile is typically about 1/3rd of that of the average U.S. automobile but, even if legislation is enacted limiting U.S. engine size thus cutting gasoline consumption to something approaching European levels, the effect of this would take about ten years to work through the system since this is the reported life span of the average U.S. automobile.

The current demand for Residual fuel oil in the U.S.A. could be associated with temporary shortages of other fuels, for example the shortage of natural gas as the result of the long argument over natural gas pricing and distribution. The demand for residual fuel oil may be expected to subside when these anomalies are rectified.

5. THE PROSPECTS FOR PETROLEUM-BASED AVIATION FUEL

Within the limits of present N.A.T.O. crude oil demands, there would appear to be significant amounts of kerosine fraction available in the European refineries although some of it may not be suitable for producing fuel to the present Jet A1 specification without further refinery treatment.

There are three aspects of the present Jet A1 specifications which need to be considered separately:-

(1) the desirability of keeping within the kerosine boiling range
(2) the extent to which present limits of carbon/hydrogen ratio might be relaxed
(3) the practicability, in aircraft operating terms, of relaxing the Jet A1 freezing point specification.

The question of the degree of fuel volatility required and the effects of carbon/hydrogen ratio in atomized spray flames have only been tackled on an empirical basis and fundamental information is lacking. It is tempting to argue that the weaker premixed primary zones of the latest generation of low emissions combustor designs will have a beneficial effect here and permit more difficult fuels to be burned cleanly. This ignores the possible importance of a rich primary zone in confering operational flexibility, particularly in military aircraft. Recent thinking (11) suggests that in primary zones stabilized by air jet entrainment, it is the entrainment appetite of the jets which actually control the quantity of air which is fed into the primary zone reversal. This flow is smaller and the resultant mixture strength in the extreme upstream region of the flame is in fact much richer than is commonly assumed. This would explain the excellent operational stability of such flames under such conditions as slam decelleration where transient flow conditions (11) could produce (as a step change) a two to one reduction in mixture strength. For a premixed, well-stirred, primary zone designed for normal operation at mixture strengths on the weak side of stoichiometric (i.e. of the type being considered for low emissions combustors), this could produce a transient mixture strength beyond the weak limit for premixed kerosine/air systems ($\phi^* = 0.45$).

The background of basic research in high pressure hydrocarbon/air flames is discussed in more detail in the succeeding lecture. It is sufficient to note here that the existing published information was concerned initially with pure hydrocarbons covering a range of carbon/hydrogen ratios and later with aviation kerosine to the Jet A1 specification. The work needs extending to higher boiling range, higher carbon/hydrogen ratio liquid fuels.

The discussions reported in (1) concluded that apart from the combustion considerations just described, increase in fuel boiling point temperature and in carbon/hydrogen ratio were also likely to have adverse effects in the engine control system. It was argued that the third important property, freezing point temperature, was of most concern to the aircraft fuel system. Possible techniques for accomodating higher freezing points fuels are discussed in (12).

Summarizing then, while there are local supply difficulties at the moment, generated by the more restricted and less suitable range of crude oils which now have to be used, it should be possible to continue using aviation fuel based on straight-run kerosine, for the short term (5 years). Beyond this, a good deal depends on the direction taken by energy demand control policies. The U.S.A. is the major fuel user here and while the future demand situation for the other N.A.T.O. countries looks much less problematic, failure to control U.S. demand development could manufacture a future problem for the rest. The N.A.S.A. move to undertake gas turbine and aircraft research and development on the effects of broadening the aviation fuel specification is welcome, both in its own context and also for the 'spin-off' which is likely to occur for diesel fuelled marine and land-based gas turbine engines.

It is important however to bear in mind the likely cost of modifying engines and aircraft (and retrospectively at that for the large existing civil fleet) to accomodate the effects of major changes in fuel specification. This will have to be compared with realistic estimates of the cost of increasing aviation fuel yield by using the wide range of conversion techniques already available in the refinery. The other factor which needs to be considered in aiming this R and D program correctly is what kind of fuel, with what combustion properties, must we be able to use in the long-term future when petroleum resources are exhausted.

6. LONG-TERM SOURCES OF AVIATION FUEL

Liquid hydrocarbons might be regarded as a very convenient and reasonably safe way of carrying, storing and using hydrogen. In recent years, a great deal has been written concerning liquified hydrogen as an aircraft fuel for the future. While the properties of hydrogen makes its combustion relatively straight-forward and free from problems, the effect of the low liquid density is such as to require a

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$$^* \phi = \text{Equivalence ratio} = \frac{\text{fuel/air ratio of mixture}}{\text{fuel/air ratio stoichiometric}}$$

somewhat differently proportioned aircraft from the familiar hydrocarbon fuelled ones and of much larger size for a given duty. The very wide stable burning range and high heat of combustion which make hydrogen attractive as a fuel would also magnify aircraft safety problems to frightening proportions and it is not proposed to deal any further with this option in the present text.

All of the sources of fossil carbon alternative to petroleum require thermal degradation and hydrogenation to produce an acceptable aircraft fuel. The fossil fuels concerned are tar sands, shale oil and coal and the author is indebted to a source of expert information in organic geo-chemistry (13) for the following treatment of the first two of these.

Tar sands consist of a mixture containing 16 to 20% oil, the remainder being rock and sand. The oil is very different from petroleum, being much heavier because the original geological containment has reached the earth's surface and all of the lighter hydrocarbon fractions have evaporated. The problems involved are almost entirely in recovery of the oil, which can be by heating or by solvent extraction. The extracted material has an empirical formula of about $CH_{1.5}$ and approximates in properties to a petroleum atmospheric residue. A previous N.A.T.O. study put the proven and probable reserves of tar sands (in Canada) at between 15 and 30 x 10^9 U.S. Barrels of oil equivalent. The projected resources were put at between 700 and 800 x 10^9 U.S. Barrels of oil equivalent although 90% of this lies too deep for surface mining.

The largest known deposit of shale oil is at Green River in Colorado, U.S.A. with other significant amounts also in Brazil, Canada, Burma, U.S.S.R. and China (10). Projected resources are 1800 x 10^9 U.S. Barrels of oil equivalent although only some 6% of this is accessible and sufficiently concentrated (seams over 9m thick and yielding at least 136 litres of oil per tonne of rock) (10) to be commercially attractive. The shale oil (kerogen) has properties which place its behaviour somewhere intermediate between petroleum and coal, its hydrogen content being about 9% by weight, compared with about 5% for coal and 13 to 15% for petroleum. Chemically, kerogen is more saturated than coal, being partly aromatized and oxygenated, with bonding to inorganic carbonates (in the rock) by long chain acid groups. The hydrocarbon has to be released from these by pyrolysis.

Both of the above materials have question marks hanging over them regarding accessibility and difficulty of recovery. The most plentiful and accessible other fossil fuel available to N.A.T.O. is coal. Coal reserves have been classified into categories representing reserves known from existing mining exploration, reserves inferred from what is known of the less well explored structure around existing mines and other probable reserves, the magnitude of which is less accurately established by other means. The numbers quoted over the past seventy years have shown considerable fluctuations, depending on the energy economy climate of the time. The figures quoted in Table 6 are taken from (5) and are intended to show total probable reserves. Also shown are values from the same source for crude petroleum and natural gas. The total N.A.T.O. reserves of hard coal, converted in heat energy terms to oil equivalent and expressed in U.S. Barrels amounts to 14 x 10^{12} Barrels, which is about ten times the probable remaining world reserves of crude petroleum.

The question of converting coal into liquid hydrocarbon fuel hinges on how this might be done and at what rate of conversion - how much oil from how much coal? There are, broadly, two types of process for doing this. In one of them, typified by (14), the coal is gasified with added oxygen and steam to give a mixture of the approximate composition ($CO + 2H_2$). This is then reacted over a catalyst to eliminate one molecule of water per molecule of CO, with the formation of a (paraffinic) hydrocarbon structure $(CH_2)_n$. The data for this process, given in (14), amount to a yield of 1 tonne of hydrocarbon product from 7 tonnes of coal input, the product being a range of materials from light hydrocarbon gases up to fuel oil. An alternative procedure involves treatment of the coal with a liquid solvent and subsequent thermal cracking and hydrogenation of the extract. Such a process, based on the earlier work of Berguis, is described in (15). This again places coal requirement at a very similar level - about 6 tonnes per tonne of hydrocarbon product. There is a good deal of research activity now in progress, particularly on the solvent extraction process, both in the U.S.A. and in Europe, most of the published papers coming from the U.S.A. Typical of the latter is (16) which contains papers first presented at the 172 nd National Meeting of the American Chemical Society and deals with all aspects of the process.

Solvent refining of coal is now achieving very high rates of extraction (90% has been mentioned). Single droplet combustion experiments have been described (17), using a range of extracts produced by the British National Coal Board. The combustion behaviour of these extracts, a pre-ignition induction period followed by a short period of a burning of volatile material and then a final period of burn-out of the carbonaceous char which is formed, has many similarities with the burning of droplets of heavy residual fuel oil containing quantities of asphaltenes. The residence times required for the complete burn-out of the solid residues of such particles are at least ten times as long as the residence times of typical present-day gas turbine combustors. Cracking and hydrogenation of the solvent extract are therefore required to give a fuel closer to the type of composition currently used, in order to avoid the formation of large solid particulate residues.

Unlike petroleum based fuels, coal extract derivatives are usually composed of ring compounds and the fully hydrogenated refined products of thermal cracking are essentially saturated bicyclic and tricyclic hydrocarbons. There is a good deal of experience in the combustion of hydrogenated napthalenes in some early British gas turbine engines in the 1950s. At the low maximum cycle pressures then used (less than 8 bars), decahydronaphthalene could be burned quite cleanly and satisfactorily, but tetrahydronaphthalene gave heavy carbon formation. The effects of the increases in maximum cycle pressure and combustor inlet temperature which have taken place since this early work require experimental examination, particularly to look at the effects of extent of hydrogenation in more detail.

There remains however a potentially serious coal supply problem. The figures of six or seven tonnes of coal per tonne of hydrocarbon product cited above will contain the coal requirements of hydrogen production reactions (presumably the reaction of coal with steam would also be used to provide hydrogen

for the solvent extraction route). They will also contain energy losses from the system during processing. More recently developments in this field have been naturally reticent (from a commercial security point of view) about process efficiencies and yields.

It is possible to take a very parochial view of the problem and to consider these processes simply as sources of aviation fuel. In this case, the size of the coal input and the industrial investment required are still large, but are of manageable proportions. This is an unrealistic view however and coal liquifaction is certain to be evaluated as an eventual replacement for the whole of the demand for premium distillate petroleum products. With the U.S.A. demand for these now running at about 500 x 10^6 tonnes per year, there would be a potential coal requirement of 3000 x 10^6 tonnes per year, even with hydrocarbon demand held at its present level. If this were in addition to the existing coal demand for other users (currently upwards of 550 x 10^6 tonnes per year), this would present a formidable task to the U.S. mining industry. Proportionally similar arguments apply to West Germany and the United Kingdom, both of whom have established coal mining industries. In both of these countries however, the coal is for the most part deep-mined and this sort of increase in extraction rate may well be impossible. There would still remain the requirements of the other N.A.T.O. countries who have little or no coal deposits of their own and who are now dependent on petroleum.

An important factor in these processes is a supply of hydrogen and a considerable reduction in coal requirement could be brought about by the provision of an external source of hydrogen, not dependent on carbonaceous fossil fuels. We can evaluate the magnitude of this hydrogen requirement approximately, as follows:- Table 5.44 of (18) lists nine coals with National Coal Board Classification numbers between 400 and 900, covering high volatile coking coals and general purpose coals. The average dry, mineral-free composition of these coals contains 84.4% carbon and 5.3% hydrogen by weight, giving an empirical formula of $CH_{0.75}$ the balance of the elemental composition analysis comprising sulphur, nitrogen and oxygen. Taking decahydronaphthalene, empirical formula $CH_{1.8}$ as typifying the desired end product, the balance of hydrogen required per gram atomic weight of carbon (12.01 grams) is 1.0584 grams of hydrogen, giving 15.188 grams of fully hydrogenated end product.

Reference (19) gives the electrochemical equivalent of hydrogen as 26.59256 amperes per gram at an electrode voltage of 2.419 volts, giving a power requirement of 64.327 watt hours per gram of hydrogen produced. This assumes an electrolysis efficiency of 100% and 95% has already been achieved using special electrolytes.

These two numbers combine to give a power requirement of 4.48 MW hours per tonne of fully hydrogenated liquid product. Thus, for the United Kingdom, with a present consumption of premium refined distillate products of about 50 x 10^6 tonnes per year, replacing this by fully hydrogenated coal extract using an external source of hydrogen by electrolysis to provide the added hydrogen would require some 224 x 10^6 MW hours for hydrogen production. This is very close to the present United Kingdom annual rate of electricity generation. For 1975, this was 272.2 x 10^6 MW hours (5) from a total installed capacity (public utility plus privately owned generators) of 78.911 GW (5). This gives an apparent plant utilization factor of 39.3% although this ignores generating plant availability which is usually taken to be in the region of 70 to 75% giving thus a utilization factor of about 55%. It is tempting to imagine the present fossil fuel fired generating plant being replaced over the next half-century entirely by nuclear plant based on fast breeder reactors and achieving a maximum utilization factor by generating hydrogen whenever the power demand curve permits.

Even if the environmental issues involved could somehow be circumvented and even give full backing by the government of the day, this would seem to be an impossible target to achieve by 2025 A.D., and no doubt very similar arguments apply to the situation in the U.S.A. and West Germany. Even this argument is based on spinning out the available world oil resources (WOAC) until 2025 A.D. or so, which is probably an extremely optimistic view to take. This treatment of the problem has been based on a severely simplified view of the future situation and in the event, the slope of demand and supply curves and the inter-relationships between the quantities involved will be much more complex. It should serve however to give us an idea of the magnitude of the task. We would seem to be faced with an unavoidable need for husbanding of fuel resources and the elimination of the less necessary uses of petroleum.

7. CONCLUSIONS

Addressing these strictly to the problem in hand, the future supplies of aviation fuels, we are driven to the following conclusions:-

(1) Collaborative effort among the N.A.T.O. countries could ease the current local U.S.A. problems in the supply of Jet A1 fuel.

(2) The controlling factor in synthesising aviation fuel, whether in the short to medium term by conversion of higher boiling petroleum distillates or in the longer term from other fossil fuel sources, is likely to be hydrogen availability.

(3) There seems to be no reasonable way in which synthetic fuel supplies adequate to meet longer term future demands at even a modest rate of annual increment, can be produced to cover the whole transport fuels area. Stricter control of supplies and elimination of the less essential needs are therefore unavoidable.

(4) U.S. petroleum demand is still growing at a much faster rate than that of other N.A.T.O. countries and control of this at an early date is essential.

(5) The most positive contribution which combustion research can make towards the future hydrogen requirement is to spell out, clearly, the relationships between hydrocarbon properties (composition, type, and volatility), flame behaviour and combustor operational performance. It will not be good enough to do this only by means of the older cut and try empirical techniques. A fundamental understanding of the interaction of fuel chemistry, flame chemistry and fluid dynamics of the combustion process is essential.

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TABLE 1

Predictions of World Oil Maximum Production Rates*

Preferred value of total economically recoverable reserves :- 1600×10^9 Barrels

	Case (a)	Case (b)
Rate of addition to reserves in Barrels/year	20×10^9	10×10^9
Maximum rates of production in Barrels/day		
(1) with no limitation of production by O.P.E.C.	86×10^6 in 1997	66×10^6 in 1993
(2) with limitation of production by O.P.E.C. to:-		
45×10^6 Barrels/day	71×10^6 in 1988	
40×10^6 " "	-	61×10^6 in 1989
33×10^6 " "	56×10^6 in 1981	54×10^6 in 1983
Rate of production in 1975	45×10^6	45×10^6
Date of decline of production to the 1975 value		
(1) with no O.P.E.C. production limit	2017	2005
(2) with O.P.E.C. limit of:-		
45×10^6 Barrels/day	2019	
40×10^6 " "		2007
33×10^6 " "	2027	2013

*From reference 10. Data excludes communist areas

TABLE 2

Energy Consumption before the Oil Crisis. 10^6 Tonnes of Oil Equivalent Data Based on United Nations Yearbooks for 1965, 1970 & 1976

	Total Energy	Decennial Average Annual Increment	Coal and Lignite	Decennial Average Annual Increment	Crude Petroleum	Decennial Average Annual Increment	Natural Gas	Decennial Average Annual Increment	Hydro and Nuclear Electricity
WORLD									
1956	2382		1317		720		300		45
1965	3654		1575		1343		653		83
1966	3857	+4.9%	1606	+2.0%	1452	+7.3%	711	+9.0%	90
1975	5602	+4.4%	1836	+1.5%	2468	+6.3%	1143	+5.8%	155
NORTH AMERICA									
1956	1001		309		407		266		26
1965	1358		314		557		460		40
1966	1437	+3.7%	330	+0.7%	584	+3.7%	495	+6.4%	42
1975	1803	+2.9%	384	+2.0%	807	+3.8%	552	+1.8%	85
WESTERN EUROPE									
1956	541		411		110		5.6		14.7
1965	732		361		324		19.6		27
1966	755	+3.4%	340	-1.9%	361	+12.6%	23	+15%	30
1975	1028	+3.5%	258	-3.3%	562	+5.7%	164	+24%	43

TABLE 3

Energy Consumption for EEC Countries and the USA for the Period 1972 to 1977. 10^6 Tonnes of Oil Equivalent

		1971	1972	1973	1974	1975	1976	1977	Average % Increment 1972-1977
EUR-9	Petroleum Products	449.56	482.50	511.52	476.81	443.38	468.41	454.76	- 1.2% per year
	Natural Gas	78.06	100.42	115.14	131.35	138.98	149.66	153.40	+ 8.8% " "
	Hard Coal	216.11	193.58	197.15	206.67	194.85	201.56	198.90	+ 0.5% " "
	Other	38.41	41.64	41.43	46.59	52.48	53.49	56.53	+ 6.3% " "
	Total	782.14	818.14	865.24	861.42	829.69	873.12	863.59	+ 1.1% " "
DBR	Petroleum Products	120.83	128.20	136.88	122.49	117.77	127.42	124.75	- 0.5% " "
	Natural Gas	16.70	21.55	26.82	32.47	34.21	35.84	38.35	+12.2% " "
	Hard Coal	73.04	67.31	65.03	68.80	57.30	59.80	59.10	- 2.6% " "
	Other	4.88	5.61	6.70	7.37	9.46	9.41	13.15	+18.6% " "
	Total	215.45	222.67	235.43	231.13	218.74	232.47	235.35	+ 1.1% " "
France	Petroleum Products	90.01	99.47	111.19	105.48	97.24	103.94	98.67	- 0.2% " "
	Natural Gas	9.69	11.48	13.46	14.05	15.67	16.84	18.47	+10% " "
	Hard Coal	30.14	26.56	25.82	28.09	26.17	29.95	28.90	+ 1.7% " "
	Other	14.12	15.34	15.11	17.39	19.44	16.01	23.40	+ 8.8% " "
	Total	143.96	152.85	165.58	165.01	158.52	166.74	168.94	+ 2.0% " "
Italy	Petroleum Products	77.96	83.12	88.87	88.69	82.46	88.38	82.50	- 0.1% " "
	Natural Gas	10.79	12.48	14.15	15.88	18.16	21.98	19.12	+ 8.9% " "
	Hard Coal	8.25	7.96	8.05	9.35	8.72	8.62	8.48	+ 1.3% " "
	Other	11.31	12.02	10.99	11.12	12.00	11.65	11.96	- 0.1% " "
	Total	108.31	115.58	122.06	125.04	121.34	130.63	122.06	+ 1.1% " "
Netherlands	Petroleum Products	22.89	24.81	25.38	22.19	20.60	24.43	22.83	- 1.6% " "
	Natural Gas	19.85	25.69	28.36	30.44	31.24	32.65	33.20	+ 5.3% " "
	Hard Coal	3.94	2.97	2.90	3.18	2.77	3.30	3.32	+ 2.3% " "
	Other	0.10	0.08	0.27	0.81	0.82	0.95	0.91	+63% " "
	Total	46.78	53.55	56.91	56.62	55.43	61.33	60.26	+ 2.4% " "
Belgium and Luxembourg	Petroleum Products	24.31	26.09	27.35	24.17	22.42	23.63	23.50	- 2.1% " "
	Natural Gas	4.70	6.02	7.32	8.62	8.45	9.05	8.95	+ 8.3% " "
	Hard Coal	11.07	8.65	11.33	12.43	9.24	10.14	9.65	+ 2.2% " "
	Other	0.04	0.15	0.47	0.21	1.90	2.68	3.12	+ 83% " "
	Total	40.12	40.91	46.17	45.43	42.01	45.50	45.22	+ 2.0% " "
United Kingdom	Petroleum Products	91.54	97.81	99.40	93.59	82.91	81.65	81.99	- 3.5% " "
	Natural Gas	16.32	23.16	25.01	29.89	31.24	33.30	35.33	+ 8.8% " "
	Hard Coal	87.67	75.66	81.19	81.82	87.48	86.60	84.99	+ 2.4% " "
	Other	7.83	8.28	8.00	9.44	8.67	10.14	11.11	+ 6.0% " "
	Total	203.36	204.91	213.60	214.74	210.30	211.69	213.42	+ 0.8% " "
Ireland	Petroleum Products	4.72	4.85	5.42	5.11	4.91	5.06	(5.06)	+ 0.9% " "
	Natural Gas	-	-	-	-	-	-	-	-
	Hard Coal	0.74	0.63	0.60	0.62	0.41	0.40	0.58	- 1.6% " "
	Other	0.13	0.16	0.19	0.25	0.18	0.22	0.25	+ 9.3% " "
	Total	5.59	5.64	6.21	5.98	5.50	5.68	5.89	+ 0.9% " "
Denmark	Petroleum Products	17.30	18.15	17.05	15.10	15.08	15.91	15.40	- 3.3% " "
	Natural Gas	-	-	-	-	-	-	-	-
	Hard Coal	1.27	1.29	2.22	2.43	2.76	2.77	3.89	+ 24% " "
	Other	-	-	-	-	-	-	-	-
	Total	18.57	19.44	19.27	17.53	17.84	18.68	19.29	- 0.2% " "
United States of America	Petroleum Products		686.20	730.69	699.35	683.71	743.99	791.79	+ 2.9% " "
	Natural Gas		536.46	535.17	515.12	474.22	481.46	466.99	- 2.7% " "
	Hard Coal		331.92	356.69	354.45	353.27	380.22	393.47	+ 3.5% " "
	Other		80.84	87.89	102.64	116.96	117.62	116.55	+ 7.6% " "
	Total		1635.42	1710.44	1671.56	1628.16	1723.29	1768.80	+ 1.6% " "

Total Energy data from U.S. Statistical Yearbook 1976

	1972	1973	1974	1975
DBR	235.76	255.27	250.29	231.34
France	153.35	163.51	160.03	146.22
Italy	112.05	118.15	119.18	117.66
Netherlands	51.39	56.09	55.21	55.27
Belgium & Luxembourg	44.18	46.83	48.32	42.17
United Kingdom	209.55	218.29	212.45	206.73
Ireland	6.99	7.00	6.87	6.78
Denmark	19.70	19.39	17.58	18.66
United States of America	1699.36	1729.42	1679.45	1644.69

Note: Other = Electricity Generation by Hydro-electric, geothermal and nuclear power.

TABLE 4

1975 Detailed Breakdown of Refinery Products

	World*	United States	World other than United States	NATO other than United States
Wt Total Products (10^6 Metric Tonnes)	2088.83	602.80	1486.03	573.61
% LPG	2.04	1.62	2.20	1.95
% Naphtha	3.03	0.52	4.04	4.15
% Motor Gasoline	24.94	46.96	15.96	18.49
% Kerosine	2.92	1.19	3.60	1.75
% White Spirit	0.10	-	0.14	0.20
% Aviation Kero-Sine (Jet Fuel)	4.23	6.79	3.19	3.25
% Distillate F.O.	22.89	22.22	23.08	26.65
% Residual F.O.	34.43	11.30	43.67	39.95
% Lubricants	1.07	1.34	0.95	0.90
% Bitumen	2.94	3.94	2.86	2.42
% Wax	0.07	0.12	0.05	0.05
% Liquid Bitumen	0.07	0.12	0.04	0.05
% Coke	1.27	3.89	0.20	0.18

*Excluding China and USSR

TABLE 5

Changes in US Domestic Production and Demand for the Four Major Types of Petroleum Product for the Period 1972 to 1977

	1972	1973	1974	1975	1976	1977
Motor Gasoline						
Domestic Production 10^6 tonnes	271.31	281.93	274.63	281.55	295.37	303.79
% of crude	48.0%	46.9%	47.0%	47.4%	45.6%	42.9%
Total Consumption 10^6 tonnes	275.41	288.28	282.37	288.33	301.41	310.05
% increment	-	+4.7%	-2.1%	+2.1%	+4.5%	+2.9%
Jet Fuel						
Domestic Production 10^6 tonnes	39.64	40.20	39.12	40.76	42.96	45.58
% of crude	7.0%	7.0%	6.7%	6.9%	6.6%	6.4%
Total Consumption 10^6 tonnes	48.90	49.56	46.75	46.84	46.51	48.85
% increment	-	+1.3%	-5.7%	+0.2%	-0.7%	+5.0%
Distillate Fuel Oil						
Domestic Production 10^6 tonnes	127.99	137.24	129.84	129.11	142.30	159.24
% of crude	22.7%	22.8%	22.2%	21.7%	22.0%	22.5%
Total Consumption 10^6 tonnes	141.77	150.48	143.47	138.75	152.33	162.79
% increment	-	+6.1%	-4.7%	-3.3%	+9.8%	+6.9%
Residual Fuel Oil						
Domestic Production 10^6 tonnes	43.53	52.90	58.29	67.28	75.02	95.12*
% of crude	7.7%	8.8%	10.0%	11.3%	11.6%	13.4%
Total Consumption 10^6 tonnes	137.78	153.74	143.77	134.13	151.78	166.05
% increment	-	+11.6%	-6.5%	-6.3%	+13.2%	+9.4%

* Average annual increment for the period for domestic Residual Fuel Oil Production = +17%

TABLE 6

NATO Fossil Fuel Reserves – 1975 (Data from Reference 5)

	Total Reserves Known And Inferred 10^9 Metric Tonnes		Natural Gas 10^{12} Cu. Metres	Crude Petroleum 10^9 M. Tonnes
	Hard Coal	Lignite		
Belgium and Luxembourg	0.25	-	-	-
Canada	97.0	11.7	1.61	0.9
Denmark	-	0.02	0.05	-
France	1.38	0.03	0.13	-
Germany (DBR)	230.0	55.9	0.31	0.07
Greece	-	1.6	0.11	0.08
Ireland	0.05	-	-	-
Italy	-	0.11	0.21	0.09
Netherlands	3.7	-	1.85	-
Norway	0.15	-	0.57	0.81
Portugal	-	0.03	-	-
Turkey	1.29	6.0	-	-
United Kingdom	162.8	-	0.82	1.3
United States	2286.0	638.0	6.46	4.4
Total	2783.0	714.0	12.0	7.65

FUTURE AVIATION FUELS
FUEL SUPPLIERS' VIEWS

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SUMMARY

Demand for aviation fuel in the period before the 1973 crisis was growing rapidly with the rapid growth of international and national high speed communications. It is therefore important to consider not only the situation in the period immediately after that crisis, but also the expected developments for the future. In this paper, developments in the potential future availability of aviation fuels from petroleum crude oils, shale oils and coal are reviewed on the basis of published data. Much of the data have been derived from statistics of the Organisation for Economic Co-operation and Development (OECD) and the Workshop on Alternative Energy Strategies (WAES). In all of the data billion is taken as 10^9.

1. MARKET TRENDS

In recent years there have been many analyses of the availability of fuels for aviation and just as many forecasts of future demands and supplies. Today, I am not going to add my own to these, but merely examine the different forecasts and draw out the common factors.

Figure 1 shows the demands for aviation fuels for the year 1960-75, drawn from OECD statistics.[1] The figures shown represent the total aviation fuel, i.e. kerosines, wide-range fuels and aviation gasolines. Demand increased at a rate of about 17% per annum until 1970 but the 1973 fuel crisis resulted in reduced availability, increased price and a reduced demand. During the fuel crisis, the airlines adopted many techniques for fuel saving and these were supplemented by developments in engine efficiency. For example, the US Dept. of Commerce reported recently[2] that in 1977 the United States passenger traffic reached 190 billion passenger miles, 6% higher than in 1976, and an increase of 5% growth is expected yearly in the next 5 years; despite this growth, the scheduled carriers consumed 80 million gallons less fuel in 1976 than in 1973.

Figure 2 shows the growth of world scheduled revenue traffic from 1967 to 1977,[3] the figures beneath the curve giving the percentage growths in that period.

International Air Transport Association (IATA) forecasts now suggest that scheduled passenger traffic will increase at about 8% per annum up to 1981. The impact of this increased traffic upon fuel demands will undoubtedly depend upon further developments in operational and engine efficiency, but it is unlikely that the same percentage improvement in these can be expected progressively and some growth in fuel demand should be expected. One complicating factor, however, is that such growth will not be uniform and growth rates in Middle East and Far East traffic may well be as high as 14%, with fuel increases as high as about 10%.

Beyond 1980 it needs a crystal ball to judge the likely developments, but a fascinating attempt was made in 1974, by Prof. Doxiadis,[4] to analyze the likely trends in the patterns of human behaviour in transportation. He considered that the probable trend will be towards the concept of Ecumenopolis - a Global City - as the ultimate extension of the spread of urban districts. Thus, the present day commuting in the USA of distances of around 100 miles, often by air (see Figure 3, taken from Doxiadis' paper), will be extended and supplemented by more frequent long-distance travel. The essential role of air travel in such a mode of life is obvious and, indeed, the success of supersonic 'planes on selected routes and of reduced-fare transatlantic flights is an indicator of a steady move in this direction.

Currently, aviation consumes a relatively small proportion of the total energy used in transportation and of the total petroleum products. Figure 4 shows the pattern for OECD for the period 1960 to 1975. The growth in consumption of motor gasoline, one of the major products, is already starting to decrease and predictions suggest that growth will continue to decrease through 1980 and that consumption will then remain at a constant volume or even decrease. Before going on to consider the long-term availability, it is pertinent to consider the adequacy of supplies of aviation fuel even at the present time. In a presentation to an SAE Aerospace Engineering and Manufacturing Meeting in Los Angeles in 1975, Scott Elstad illustrated some of the problems facing the USA refineries in two separate areas West and East of the Rockies (Figures 5 and 6). These show the dependence of turbine fuel availability upon the method of operation of the refineries. For example, west of the Rockies, if the refineries are operated to maximize the production of gasoline or of furnace and diesel oils, there is a significant reduction in the kerosine availability, leading to a need to import products which, since some of these are derived from Alaskan North Slope crudes, may be somewhat less attractive in quality. This interaction between the different products highlights the integrated nature of oil supplies. I shall return to this particular point later in the presentation.

Other complications in the local availability can be dictated by local climatic operating conditions. For example, for many years the fuel in main demand in Canada has been the wide range JP4; one reason for this is the need to start engines after prolonged idleness at temperatures that may be as low as -30°C. The high volatility of JP4 has caused concern about safety and vapour loss in some instances and, as a consequence, consideration is now being given to a fuel that is intermediate in volatility between kerosine and JP4. Thus, it can be seen that it becomes difficult to generalize worldwide, both from the point of view of local supply-and-demand and from that of local specifications.

2. WORLDWIDE ENERGY SOURCE AVAILABILITY

We have seen how the proportion of the crude oil barrel used for aviation purposes is small, of the order of 4% in non-American areas and possibly up to 7% in the USA (Figures 7a and 7b). The total potential availability of the kerosine fraction in petroleum crudes is, however, significantly higher, with much being used for domestic and industrial heating, but the total quantity of fuel will depend upon the overall availability of crude oil.

2.1 Petroleum crude oil

Estimates of ultimately recoverable oil reserves tend towards 2000 billion barrels (270 billion metric tonnes), of which three quarters might be outside the USSR, Eastern Europe and China. In the recent WAES survey this was taken as a central figure, although higher and lower alternatives were also considered. The rate at which proven reserves are increasing is historically about 18 billion barrels per year and in the WAES study, assumptions of 20 billion barrels and 10 billion barrels were taken respectively for the high and low levels. Figures 8 and 9 show the supply-and-demand for oil under two scenarios: C1, in which demand growth and annual additions to reserves are relatively high, and D8, in which these factors are relatively low. The highest profile in each scenario assumes that production is limited only by the technical constraints of the ratio of reserves to production.

The crosses in Figures 8 and 9 assume OPEC production limits of 45 and 40 million barrels/day respectively, which might be adopted for economic reasons or to conserve resources. Assuming no production limits by countries outside OPEC, the result is a plateau in world oil output through the 1990s before technical limitations force the curves down early next century.

The dotted curves in Figures 8 and 9 show the production resulting from a hypothetical restriction of output by some Arabian countries to little more than present amounts, giving a mean production maximum by OPEC countries of 33 million barrels per day. The result would be a levelling of world oil production in the early 1980s and a failure to meet projected demand much earlier than under the other production profile.

Thus, if the consumption of oil grows as expected, WAES conclude that at some time during the next twenty years the supply of oil will fall short of the estimated demand.

On the other hand, Odell and Rosing[5] suggest that North Sea oil reserves have often been underestimated and that politics and institutions often dictate the rate of production. They also argue that the annual rate of energy usage will be diminished by the demand response to higher energy prices and by deliberate changes in the structure of society. However, they agree that by the second quarter of the 21st century, coal could become the single most important energy source, given the development of new technologies on both the supply and demand sides. They consider that such developments could largely eliminate the demand for oil imports within Western Europe. Indications of the downturn in demand for oil products are seen already in the over-capacity of refineries in Western Europe,[6] illustrated in Table 1, although this picture could change with a resurgence in the economy. Thus, as foreseen by V.E. McKelvey of the US Geological survey, the general picture of petroleum oil supplies is still that of an eventual deficiency of supply over demand, the only uncertain factor is the actual timing.[7] There is still a need, therefore, to examine the alternative sources of energy and their potential in helping to meet the demands of the aviation market at some time between 1995 and 2025.

2.2 Shale oil

In terms of heating value, next to coal, oil shale represents the most plentiful fossil fuel resource in the United States.[7] It is composed of insoluble organic material (kerogen), soluble organic material (bitumen) and inorganic materials. The oil shale contains about 80-85% mineral matter and about 15-20% organic material, of which about 90% is kerogen. The kerogen molecules have a molecular weight of over 3000 and form the continuous phase of a rich shale and act as the cohesive binder. This organic material within the shale is thermally unstable and decomposes on heating to form gaseous and liquid products and a coke-like residue.

Outside the USA, significant amounts of oil shale are found in Brazil, the USSR and China, with smaller quantities in other countries such as Sweden and Scotland. The greatest exploitation of oil shale reserves to date has been in the USA and it is instructive, therefore, to look at the achievements there, the problems faced and the potential for the future.

The kerogen component of oil shale is heavy, very viscous and cannot be pumped at ambient temperatures. It contains significant quantities of nitrogen and, at times, some arsenic; furthermore, it contains more oxygenated compounds than does crude petroleum. Before the development of the petroleum industry in the USA, oil shale had been used to produce oils and waxes, but these early developments were supplanted by the availability of cheaper petroleum crude oils.

Oil shales occur throughout the USA, the best known (Eocene Green River formation) covering an area of about 17 000 square miles and representing some 2-4 trillion barrels ($0.3\text{-}0.6 \times 10^{12}$ m^3) of oil. However, Devonian deposits existing in the Eastern and Midwestern parts are even greater and underlie an area of over 400 000 square miles. The different deposits are different in character, the Western shales yielding about 25 US gallons of oil per ton of rock whilst the Devonian shales yield typically 10 or less gallons per ton, although producing more light hydrocarbon gases than the Western shales.

Surface retorting processes have been in use for many years at many locations around the world but the bulk of rock to be handled is an inevitable handicap to its economical larger-scale exploitation. As a consequence, considerable development effort is now being expended on in situ retorting and direct hydrogasification, and a maximum worldwide production of about 2 million barrels of oil in year 2000 is projected, mainly in the USA.

Conversion of kerogen into liquid products is effected by pyrolysis at 900°F (480°C) or higher, and the relative proportions of oil, gas and coke vary with the pyrolysis temperature, pressure, rate of heating, the nature of the atmosphere surrounding the oil shale and, to some extent, the organic content of the raw shale. The higher operating temperatures produce more gas and relatively less oil, whereas high pressure (more than 500 lbf/in^2) reduces oil yields significantly; however, oil produced at higher pressure has a lower pour point, lower density and lower viscosity than oil produced at low pressure.

2.3 Coal

Table 2 shows the known world energy reserves of coal, estimated in 1971, together with potential future reserves. These figures are expressed in billion tons of coal, convertible to billion tons of oil equivalent by multiplying by 0.7, and from these it will be seen that the coal reserves are many times the potential oil reserves. These relationships between coal and oil reserves have been supported by more recent figures. Compared to oil, gas and electricity, coal has been dirty and awkward to distribute and use. Because of this, its share in total energy declined steadily as industries and private consumers switched to more convenient and cleaner fuels, leaving coal, in many countries, to supply little more than power stations and steel industries. The future developments must then be concerned with reversing this trend, substituting coal for oil and gas in electricity generation and for process heating in industry, possibly with direct conversion of coal into oil and gas. Unfortunately, conversion is costly, both in financial terms and in energy terms, so it is essential to develop to the maximum clean methods of handling and burning coal. Developments in pulverized coal firing and in fluidized beds are promising, as are techniques for preparing, handling and firing suspensions of coal in oil.

In order to satisfy also environmental conservation requirements, it will be necessary to apply extensive washing and blending to reduce solids and sulphur components. Even so, there will still need to be widespread use of flue-gas cleaning plants.

The large scale conversion of coal into liquid fuels has been practised for many years. In Germany and Japan during World War II, processes based on low-hydrogen consumption (Pott-Broche system) and high-hydrogen consumption (Bergius process) were used extensively to produce aviation and transportation fuels. The generalized flow sheet for such processes[8] is as shown in Figure 10. The low-hydrogen processes are usually non-catalytic, operating at a low temperature (about 750°F, 400°C) and under just enough pressure to maintain the solvent as a liquid, using mechanical means for separating the solvent and extract from the undissolved coal particles. On the other hand, the high-hydrogen processes are catalytic, operating at a higher temperature (800-850°F, 425-445°C) and higher pressures (up to 10 000 lbf/in^2 H_2). These processes, especially the latter, are now being developed to produce either a synthetic crude oil as a feedstock to conventional refineries or a low-sulphur distillate fuel oil, and much research is in hand to prove the feasibility of the processes and to develop their economics.

South Africa has depended extensively on liquid fuels derived from coal for a number of years and the processes they follow are described in some detail later in the presentation. They have been applied extensively, particularly for gasoline and chemical feedstock.

2.4 Tar sands

Canada has huge deposits of oil, or tar sands at Athabasca, Alberta and oil extraction from these is due to start early this year[9]. These oil sands are the world's richest and are estimated to contain 600 billion barrels of oil. Because of the cost of extraction they have not been economic to mine until the oil price increases of 1973. A syncrude consortium was formed to win the oil and up to £4 billion have been invested in plant, with an estimated future production leading up to 130 000 barrels per day by 1980. The ratio of tar to sand is 12:84, 4 per cent being other minerals, and cracking of the extracted oil gives two streams - naphtha and gas oil (diesel).

3. QUALITY OF AVIATION FUEL DERIVED FROM DIFFERENT SOURCES

3.1 Crude oil

Current aviation fuel specifications are listed in Tables 3a, 3b, and 3c. Whilst early developments of aircraft gas turbine engines were based on the use of kerosine type fuels, expected extension of demands for military emergencies were met by the creation of the wide-range gasoline-type fuel embracing also naphtha components. Such fuels have been used very effectively and satisfactorily for many years, for both military and commercial applications. However, because of concern about loss of fuel vapour and about safety, especially during military operations, moves have been introduced recently to replace the wide-range fuel by one nearer in specification to kerosine.

Many of the specification items are concerned with engine or aircraft performance but are not in themselves restrictive to supply, though requiring extra refinery treatment. In a number of cases, however, relaxation of the actual levels of particular properties could extend the proportion of the crude oil suitable for aviation engines, especially if other applications of petroleum products could be satisfied by alternative means. Figure 11 shows typical distillation ranges of a number of conventional products; the proportion of the crude oil barrel falling into the kerosine boiling range differs with the method of operating the refineries: in North America, where refinery operation is geared to a maximum production of gasoline, the proportion of kerosine is around 7%, whilst in other areas, where a large production of fuel oil has traditionally been called for, the proportion of kerosine has been around 4%. These kerosines have, of course, been used also for other purposes, such as domestic and lighting, and to secure them for aviation purposes alone would demand alternative energy sources for these other applications. From the type of refinery operation in the USA, it follows that there is further scope for kerosine production in other areas by maximizing the yield of gasoline. Indeed, the trend outside the USA in recent years has been towards reducing fuel oil generation, because of reduced demand from industry for fuel oil (induced by economic factors and energy conservation) and because it made good financial common sense.

Within the current kerosine specifications, the suitability of aviation fuels derived from some particular crude oils can be limited by the specified aromatics contents or freezing points. Already the aromatics contents of fuels from certain crudes have exceeded the originally specified 20% and a relaxation to 22% has been accepted; in other cases, a relaxation of freezing point, to -47°C instead of -50°C, is being sought. Arguments against these relaxations were advanced by the engine manufacturers and some airlines, although evidence has been provided to demonstrate that penalties are not truly significant. Further extension of specifications, to incorporate a wider range of the crude oil barrel, could cover lower boiling material than kerosine or higher boiling material or both. The limit in downward movement of initial boiling point would be set either by the volatility of the fuel (with its implicit penalties of loss of fuel vapour at altitude and of reduced flash point, with a need for increased safety precautions in handling) or by problems in combat. These have been faced with JP4 or Jet B and are widely known.

Increases in the final boiling point would be accompanied by a need to adapt the combustion system to avoid the emission of unburnt hydrocarbons or of smoke, by a raising of the freezing point of the fuel, by a need, perhaps, for hydrogenation to reduce sulphur contents and possibly, by further additional refinery treatment to meet other constraining performance factors such as thermal stability. Hydrogenation and other refinery treatments are feasible but would be expensive and energy intensive and would require additional capital investment.

Thus, it is feasible to extend the quantity of aviation fuels from crude oils, although at some expense and with impact upon the proportion of the crude available for other applications. Inevitably, such redistribution of petroleum in favour of aviation applications, representing only a relatively small proportion of total demand, would necessitate an imposed regulation or a financial inducement or both.

3.2 Fuels derived from shale oil

Whilst shale oils have been a source of gasolines and other products, only limited work has been carried out on the specific derivation of aviation fuels. This has been sponsored by the US Air Force[10,11] and results of the work to date suggest that crudes derived from shale oils could form a suitable basis for the production of aviation turbine fuels. The shale oil processes for the different types of shale are somewhat similar to one another; the TOSCO II process uses hot solids recirculation to provide the heat to the retort, whilst the Union, Panaho and US Bureau of Mines (USBM) processes are modifications of gas combustion retorting and depend on the heat contained in the flue gases (from burning some of the gases) to separate the oil. In situ processes, such as those developed by Garrett and the USBM, involve explosives to break up the shale rock beds and then partial combustion of the shale oil to increase the bed temperature to drive the oil to the surface. The in situ techniques tested to date require a significant (15-45%) void volume to achieve good recovery of oil and thus will involve a fair amount of above-ground retorting as well as disposal of spent shale. Inevitably, therefore, such processes will be costly and will require considerable large-scale capital investment and development. However, in the long-term interest of their availability as energy resources for aviation applications, it is essential also to look at the suitability of the product produced.

In the US studies it was concluded that satisfactory jet fuel, approaching current specifications, can be produced by hydrotreating shale oil; some reduction in fuel boiling point may be needed in order to meet the freezing point specifications. The raw shale oil has a very high nitrogen content (2%) but this has been shown to be capable of removal by hydrotreating.

The recommendations of the studies suggest that the shale oil should be topped to remove the bottom fraction containing particulates and asphaltenes. The 600-900°F (315-480°C) fraction would then be processed through hydrocracking or catalytic-cracking. Before catalytic hydrotreating, a preliminary hydroprocessing step is required to remove nitrogen and thus prevent poisoning of the catalysts; this treatment will also remove much of the sulphur and the oxygenated compounds present. The final products will probably be compatible with fuels derived from petroleum crudes, although little checking of this aspect has been carried out.

3.3 Fuels derived from coal

3.3.1 General approaches

There are three approaches[12] available for production of liquid hydrocarbons from solid fuels: (1) gasification-synthesis, involving gasification of the coal to carbon monoxide and hydrogen, with subsequent catalytic synthesis by the Fischer-Tropsch process to hydrocarbons or alcohols (methanol or butanol); (2) hydrogenation, involving the addition of hydrogen, to remove oxygen, sulphur and nitrogen and to increase the H/C ratio of the coal; (3) thermal cracking/pyrolysis/low-temperature carbonization, involving splitting the solid fuel into hydrocarbons, water and carbonaceous residue by heat alone.

The coals found in different geological deposits differ not only in their ultimate analysis - percent carbon and hydrogen, oxygenated compounds and mineral matter (ash) - but also in the nature of the carbonaceous components - typically coal, anthracite and graphite. The term "rank" is often used to qualify the type of coal, the higher ranks indicating higher percentages of carbon and lower percentages of hydrogen, oxygen and volatile matter. The amount of oils and tars recoverable by low-temperature carbonization is relatively constant in the low rank coals but drops rather suddenly as the rank increases.

Rank, however, is not always indicated reliably by analytical data and a better parameter is the reflectance of the coal constituent, or "maceral", vitrinite under reflected light of a microscope. Vitrinite is the main constituent of bright coal, the other macerals being exinite and inertinite. Exinite is similar to kerogen in oil shales and, chemically, has a highly naphthenic structure with associated aromatic and nitrogen-sulphur heterocyclic ring systems. It gives a low-temperature oil yield of about 40-50%.

Vitrinite contains less hydrogen and more oxygen than does exinite, whilst its carbon content is slightly higher. It contains aromatic and aliphatic compounds, the percentage of hydrogen in aromatic

configurations increases with rank from 25-65%. Volatile matter in vitrinite is 30-40% and the low-temperature oil/tar yield is about 12-14%.

Inertinite, the last group, is rather complex, with a rather variable chemical composition and a low pyrolysis oil yield.

Table 4 shows the composition of a number of liquids generated from selected coals on plants and pilot plants. It will be seen that the liquid yields are all relatively modest and that furthermore their aromatics contents are fairly high.

3.3.2 USA

In the USA, some work has been carried out on the production of jet fuels from coal and a conclusion reached that most of the critical jet fuel specifications can be met. The specific gravity would be higher than specification but hydrogen content could be raised to between 13.5 and 14.0%, thus making the fuels better in combustion properties. There would be some difficulty in meeting smoke point specifications, and perhaps freezing point, whilst additional treatment may be required to ensure good thermal stability and low nitrogen contents.

3.3.3 South Africa

The SASOL plant in South Africa is now about the only commercial scale operation producing liquid fuels and this merits special consideration. The coal reserves on which it is based are extensive and considered adequate for about 100 years, although they are of low grade with an ash content of up to 30%, 8% moisture and 23% volatile matter. The plant is run in two stages, the first being a modern form of the German fixed bed process, with about 60% synthesis gas; the second stage Kellog's entrained catalyst process is used to process the remainder of the synthesis gas, with tail gas from the first stage and recycle gas from the second.

In the fixed-bed process, a kerosine cut is normally made but is not sold as turbine fuel. Its olefin content is high (25-30%) and whilst hydrogenation could produce a stable fuel, its freezing point would probably be too high. This fuel is, however, suitable for diesel fuel but is used largely for chemical feedstock.

Kerosine from the fluidized-bed process is again not directly suitable as a turbine fuel because of its high olefin content but hydrogenation could yield a very suitable fuel high in branched chain products. An estimate gives the yield of jet fuel as about 25-30% of the synthesis products. Undoubtedly, most of the South African liquid fuel production from coal is taken up by motor gasoline.

The overall economics of the SASOL process are not good and, because of this, all jet fuel in South Africa is obtained from crude oil.

3.3.4 United Kingdom

Work by the National Coal Board in the United Kingdom has been directed to the digestion and extraction of coals with anthracene-oil type solvents and with supercritical vapours. These approaches have been shown to be feasible, although much more development is required.

Early in the 1960s, attention was drawn to the high volumetric calorific value of hydrocarbon fuels derived from creosote oils, and early USA work was followed up in France by the French Coal Research organization (CERCHAR). Table 5 gives the properties of a jet fuel (produced by them on a development scale) which, it is believed, was tested on an experimental basis. This work was not followed through, however, because of the low availability of coal tar as a feedstock, relative to crude petroleum, and because of adverse economics.

Thus, most of the technology for converting coal into liquid fuels already exists, although most of the application of this technology, earlier in Germany, in the USA and in South Africa, has been directed towards the motor fuel market. Optimization of processes to produce turbine fuels is quite possible, although the high nitrogen contents of some of the fuel produced can be a problem.

4. SUMMARY OF NON-PETROLEUM CRUDE OIL POTENTIAL

Undoubtedly the potential availability of energy sources other than petroleum crudes is enormous, and we have seen how acceptable aviation turbine fuels can be produced from shale oil, with suitable treatment, and also from coal. However, aviation is a highly international activity and as such demands availability of fuels world wide. The ABC world airways guide, for example, lists 4000 cities. They vary greatly in their activities and correspondingly in their fuel throughput, from Chicago with a throughput of several million gallons per day down to small country airfields where daily throughputs may be as low as a few thousand gallons. However, they all have in common a need for a fairly constant quality of fuel, with regular and reliable delivery to the airfield and consistent maintenance of quality at the airfield and through the delivery to the aircraft. Already many oil companies are involved in the supply of petroleum based fuels, exercising considerable care to ensure compatibility of their operations and of their fuels. The established fuel specifications are carefully framed to ensure that the composition and properties of the fuel meet the needs of the aircraft, and other papers in this series will be examining how these specifications could be broadened to increase the overall fuel availability without serious detriment to the aircraft and their engines. Increases in the permitted boiling points, in the aromatics contents and in freezing points would all lead to greater flexibility in the supply. Relaxation of the thermal stability requirements and in the sulphur limits might also be beneficial in the long term.

Shale oil and coal sources are large but are in general localized and in view of the very large capital investments required to process these materials, there is considerable logic in regarding them merely as pools of additional crude oil supply rather than in relying upon their suitability for individual products - except in cases of dire emergency, when local supplies of petroleum crudes were not available.

The cost of fuel is a significant part of the direct operating costs of aircraft. For example, some reports suggest percentages as high as 47 (Table 6 and Figure 12). The recovery of shale oil and of coal both involve considerable site activity and the likely costs of the syncrudes produced from them are quoted in Table 7.

As dependence for fuel supplies upon these sources increases, it is clear that the average cost of fuel must increase. Even if legislation were introduced to restrict the use of petroleum crudes to selected priority areas, such as aviation, those applications obliged to consume syncrude derived products are all likely to be contributory to the whole of the aviation industry through manufacturing, through power generation and through associated surface transportation. Hence, overall fuel costs will, on the longer term, tend towards a common base, independent of their source. Because of the special sensitivity of aircraft and the need for carefully handled and segregated products for them, it is highly logical that the aviation industry may be required to bear a somewhat higher proportion of the overall cost. Thus, the bad news for the aviation industry is that they should not expect fuel prices to decrease, although, in turn, the good news is that longer term supplies should be available.

What is the future prospect for the industry therefore? Already developments in engine and airframe technology, improved operating techniques and better route planning have shown considerable benefit in fuel usage. Future developments along similar lines should continue, even though gains in overall fuel economy can only be expected to diminish.

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Table 1

Refinery utilization

Capacity / Period	Barrels per day						
	US 16.45×10^6	Japan 5.35×10^6	W. Europe* 18.41×10^6	UK 3.02×10^6	W. Germany 3.12×10^6	France 3.48×10^6	Italy 4.46×10^6
	%	%	%	%	%	%	%
1974	85	84	72	76	72	78	62
1975	84	76	58	64	59	62	46
1976 Q1**	84	82	62	65	60	75	49
Q2	86	77	61	65	62	66	48
Q3	90	76	64	62	69	72	51
Q4	91	83	68	70	69	76	53
1977 Q1	87	83	66	65	67	75	52
Q2	88	78	58	62	62	62	47
Q3	90	78	n/a***	59	66	68	47

* Belgium, France, Italy, Netherlands, Spain, UK, W. Germany.
** Q1-Q4 refer to 1st-4th quarter of the year.
*** Not available.

Table 2

World energy reserves: variation in estimates

		Present known			Potential future [2]		
		Reserves	Life at 1971 [1] consumption rates	Life at future consumption rates	Reserves	Life at 1971 [1] consumption rates	Life at future consumption rates
Oil	Lowest	80×10^9 tons	32	16	250×10^9 tons	100	30
	Highest	90×10^9 tons	36	18	360×10^9 tons	140	40
Coal	Lowest	130×10^9 tons	60	30	1100×10^9 tons	500	150
	Highest	2200×10^9 tons	1000	190	4800×10^9 tons [3]	2200	250
Natural gas	Lowest	34×10^{12} m^3	33	15	90×10^{12} m^3	90	25
	Highest	48×10^{12} m^3	45	19	340×10^{12} m^3	330	40
Uranium	Lowest	0.9×10^6 tons [4]		16/(50-100) [5]	1.3×10^6 tons		20/(500-100) [5]
	Highest				3.2×10^6 tons [6]		37/(50-100)
Shale/tar sand	Lowest	97×10^9 tons	39	Extend oil by 9	280×10^9 tons	110	Extend oil by 10
	Highest	120×10^9 tons	48	Extend oil by 11	500×10^9 tons	200	Extend oil by 17

Notes

Units: Oil, and oil shale and tar sands, are expressed in billion (10^9) tons of oil.
Coal is expressed in billion tons of coal (multiply by 0.7 to give billion tons of oil equivalent).
Natural gas is expressed in trillion (10^{12}) cubic metres (multiply by 0.86 to give billion tons of oil equivalent).
Uranium is expressed in million (10^6) tons of uranium.
Life is in years.

(1) 1971 consumption rates assumed are: Oil: 2500 MTOE [7]; Gas: 900 MTOE; Coal: 1500 MTOE.

(2) Potential future reserves are usually estimates of recoverable reserves, allowing for improvements in technology of extraction and price rises, unless otherwise stated.

(3) Several sources quote 7600 billion tons of coal as potential total reserves, which is much higher than recoverable reserves.

(4) Known reserves recoverable at less than $20/kg.

(5) The life of uranium resources is considerably increased when fastbreeder reactors are considered, rather than existing light water or similar generation reactors (hence two figures for life in the table). Due to uncertainties in the future development of nuclear power the lifetimes quoted are particularly speculative.

(6) Reserves of 3.2 million tons of uranium assume a recovery cost of not more than $30/kg. However, it has been estimated that 60 million tons are available at costs up to $200/kg. In addition there are in sea water some 4 billion tons of uranium which are inaccessible with present technology and economic conditions.

(7) MTOE = million tons of oil equivalent.

Table 3a

SUMMARY OF SPECIFICATION REQUIREMENTS FOR JET A-1, KEROSINE TYPE, AVIATION TURBINE FUELS

PROPERTIES		JET A-1 SPECIFICATIONS				TEST METHODS	
		DERD 2494 Issue 7 August 1971 and Amendment 2 March 1976	IATA Guidance Material Amend 3 Dec. 1975	ASTM D1655-75	AFQRJOS "Check List" Issue 7 March 1976 (See note 5)	IP	ASTM
		Kerosene Type	Kerosene Type	Jet A-1	Jet A-1		
COMPOSITION							
Total acidity, mg KOH/g	max	0.012	-	-	0.012	273	-
Total Acidity, mg KOH/g	max	-	0.10	0.10	-	-	D974 or D3242
Aromatics, % vol.	max	20	20	20	20	156	D1319
Olefins, % vol.	max	5	-	-	5	156	D1319
Sulphur, total % wt.	max	0.20	0.30	0.30	0.20	107	D1266
Sulphur, Mercaptan, % wt	max	0.001	0.001	0.003	0.001	104	D1219 or D3227
OR Doctor Test	max	Negative	Negative	Negative	Negative	30	D484
VOLATILITY							
Distillation						123	D86
Initial Boiling Point, °C		Report	-	-	Report		
Fuel Recovered, % vol. at 200°C (392°F)	min	20	-	-	20		
10% vol. at °C (°F)	max	-	204 (400)	204 (400)	204 (400)		
20% vol. at °C		Report	-	-	Report		
50% vol. at °C		Report	Report	Report	Report		
90% vol. at °C		Report	Report	Report	Report		
End Point, °C (°F)	max	288 (550)	288 (550)	300 (572)	288 (550)		
Residue, % vol.	max	1.5	1.5	1.5	1.5		
Loss, % vol.	max	1.5	1.5	1.5	1.5		
Flash Point, Abel Method, °F (°C)	min	100 (38)	-	-	100 (38)	170	-
Flash Point, TAG Method, °F (°C)	min	-	100 (38)	100 (37.8)	(105 (40.6))	-	D56 or D3243
Specific Gravity at 60°/60°F	min	0.775	0.775	(0.775)	0.775	160	D1298
	max	0.830	0.839	(0.840)	0.830	160	D1298
Gravity, °API	min	-	37	37	39	-	D287
	max	-	51	51	51	-	D287
FLUIDITY							
Freezing Point, °C (°F)	max	-50 (-58)	-50 (-58)	-50 (-58)	-50 (-58)	16	D2386
Viscosity at -30°F (-34.4°C), cSt	max	15	15	15	15	71	D445
COMBUSTION							
Calorific Value, net, BTU/lb	min	18 400	18 400	18 400	18 400	12 or 193	D240, D1405 or D2382
OR Aniline Gravity Product	min	5 250	(5 250)	(5 250)	5 250	2 & 160 (193)	D611 and D1298 (D1405)
Smoke Point, mm	min	20 (19)	-	-	-	57	D1322
Luminometer Number	min	-	45	45	45	-	D1740
OR Smoke Point, mm	min	-	25	25	25	-	D1322
OR (Smoke Point, mm	min	-	20	20	20	-	D1322
(PLUS Naphthalene Content, % vol.	max	-	3	3	3	-	D1840
CORROSION							
Copper Corrosion, Classification	max	1	1	1	1	154	D130
Silver Corrosion, Classification	max	1	-	-	1	227	-
STABILITY							
Thermal Stability by :-							
CFR Coker (Preheater Temp. 300°F, Filter Temp. 400°F) (Fuel Flow 6lb/hour, Duration 300 min)						197	D1660
Change in Pressure Drop in 5 hours, inches Hg	max	-	3	3	-		
Preheater Deposit, classification	max	-	< 3	< 3	-		
OR Alcor JFTOT (Max Heater Tube Temp. 260°C) (Fuel System Pressure 3.45 MN/m²) (Fuel Flow 3 ml/min, Duration 150 min)		(See Note 1)			(See Note 1)	323	D3241
Filter Pressure Differential, mm Hg.	max	25	25	25	25		
Tube Rating (visual), Classification	max	< 3	< 3	< 3	< 3		
CONTAMINANTS							
Copper Content, µg/kg (See Note 2)	max	150	-	-	150	225	-
Existent Gum, mg/100 ml	max	7	7	7	7	131	D381
Water Reaction						289	D1094
Interface Rating	max	1b	1b	1b	1b		
Separation Rating	max	2	2	2	2		
Water Separometer Index Modified	min	85 (See Note 3)	-	-	85 (See Note 3)	-	D2550
ADDITIVES							
Anti-oxidant, mg/1							
Hydrotreated Fuels	min	8.6 Mandatory	Optional	Optional	8.6 Mandatory		
	max	24		24	24		
Non Hydrotreated Fuels	max	24 Optional	Optional	24 Optional	24 Optional		
Metal Deactivator, mg/1	max	5.7 Optional	Optional	5.7 Optional	5.7 Optional		
Corrosion Inhibitor (See Note 4)		By Agreement	By Agreement	By Agreement	By Agreement		
Anti Static Additive (ASA-3), by agreement mg/1	max	1.0	1.0	1.0	1.0		
Conductivity - at time/temperature of delivery to aircraft if ASA-3 present cu (pS/m)	min	50	50	50	50	274	D2624
	max	300	300	300	300		

NOTES: (1) Alcor JFTOT method mandatory after 1/4/76

(2) Only for fuels treated by "copper sweetening" process

(3) 70 min. if ASA-3 used.

(4) Details of approved Corrosion Inhibitors and concentrations can be obtained by reference to the specification concerned.

(5) Aviation Fuel Quality Requirements for Jointly Operated Systems

Table 3b

SUMMARY OF SPECIFICATION REQUIREMENTS FOR JET B/JP4 WIDE CUT TYPE AVIATION TURBINE FUELS

PROPERTIES		JET B/JP4 SPECIFICATIONS					TEST METHODS	
		DERD 2486 Issue 8 Aug 1975 and Amendment 2 March 1976	IATA Guidance Material Amended Jan. 1975	ASTM D 1655-75	MIL - T - 5624 K April 1976	AFQRJOS "Check List" Issue 7 March 1976 (See note 7)	IP	ASTM
		Wide Cut Type	Wide Cut of JP4 Type	Jet B	Grade JP4	Jet B		
COMPOSITION								
Total Acidity, mg KOH/g	max	0.012	-	-	-	0.012	273	-
Total Acidity, mg KOH/g	max	-	0.10	-	0.015	or 0.015	-	D974 and D3242
Aromatics, % vol.	max	25	20	20	25	20	156	D1319
Olefins, % vol.	max	5	-	-	5	5	156	D1319
Sulphur, total % wt.	max	0.30	0.30	0.30	0.40	0.30	107	D1266
Sulphur, Mercaptan, % wt	max	0.001	0.001	0.001	0.001	0.001	104	D1219 or D1323
OR Doctor Test	max	Negative	Negative	Negative	Negative	Negative	30	D484
VOLATILITY								
Distillation							123	D86
Initial Boiling Point, °C		Report	-	-	Report	Report		(See Note 1)
Fuel Recovered, 10% vol. at °C		Report	-	-	Report	Report		
20% vol. at °C (°F)	max	143 (290)	143 (290)	143 (290)	145 (293)	143 (290)		
50% vol. at °C (°F)	max	188 (370)	188 (370)	188 (370)	190 (374)	188 (370)		
90% vol. at °C (°F)	max	243 (470)	243 (470)	243 (470)	245 (473)	243 (470)		
% at 400°F (204.4°C)		Report	-	-	-	Report		
End Point, °C		Report	-	-	270 (518)	Report		
Residue, % vol.	max	1.5	1.5	1.5	1.5	1.5		
Loss, % vol.	max	1.5	1.5	1.5	1.5	1.5		
Specific Gravity at 60°/60°F	min	0.751	0.751	(0.751)	(0.751)	0.751	160	D1298
	max	0.802	0.802	(0.802)	(0.802)	0.802	160	D1298
Gravity, °API	min	-	45	45	45	45	-	D287
	max	-	57	57	57	57	-	D287
Reid Vapour Pressure, lb/in²	min	2.0	-	-	2.0	2.0	69 or 171	D323 or D2551
	max	3.0	3.0	3.0	3.0	3.0	69 or 171	D323 or D2551
FLUIDITY								
Freezing Point, °C (°F)	max	-58 (-72)	-50(-58)	-50 (-58)	-58 (-72)	-58 (-72)	16	D2386
COMBUSTION								
Calorific Value, net, BTU/lb	min	18 400	18 400	18 400	18 400	18 400	12 or 193	D240 or D1405 or D2382
OR Aniline Gravity Product	min	5 250	(5 250)	(5 250)	5 250	5 250	2 & 160(193)	D611 & D1298
Hydrogen Content % wt	min	-	-	-	13.6	-	-	D1018 or D3343
Smoke Volatility Index	min	54 (52)	-	-	-	54(52)	57 & 123	(D86 & D1322
Luminometer Number	min	-	45	45	-	45	-	D1740
OR Smoke Point, mm	min	-	25	25	20	25	-	D1322
OR (Smoke Point, mm	min	-	20	20	-	20	-	D1322
(PLUS Naphthalene Content, % vol.	max	-	3	3	-	3	-	D1840
CORROSION								
Copper Corrosion, Classification	max	1	1	1	1b	1	154	D130
STABILITY								
Thermal Stability by:-								
CFR Coker (Preheater Temp. 300°F, Filter Temp. 400°F, Fuel Flow 6lbs/hour, Duration 300 min)							197	D1660
Change in Pressure Drop in 5 hours, Inches Hg	max	-	3	3	-	-		
Preheater Deposit, Classification	max	-	< 3	< 3	-	-		
OR Alcor JFTOT (Max Heater Tube Temp. 260°C)							323	D3241
(Fuel System Pressure 3.45 MN/m²)		(See Note 2)			(See Note 2)	(See Note 2)		
(Fuel Flow 3 ml/min, Duration 150 min)								
Filter Pressure Differential, mm Hg	max	25	25	25	25	25		
Tube Rating (visual), Classification	max	< 3	< 3	< 3	< 3	< 3		
CONTAMINANTS								
Copper Content µg/kg (See Note 3)	max	150	-	-	-	150	225	-
Existent Gum, mg/100ml	max	7	7	7	7	7	131	D381
Particulate matter, mg/litre	max	-	-	-	1.0	-	216	D2276
Filtration Time, mins.	max	-	-	-	15	-	-	(See Note 4)
Water Reaction							189	D1094
Interface Rating	max	1b	1b	1b	1b	1b		
Separation Rating	max	2	2	2	1	2		
Water Separometer Index Modified	min	85 (See Note 5)	-	-	70	85 (See Note 5)		D2550
ADDITIVES								
Fuel System Icing Inhibitor % vol.	min	-	-	-	0.10 Mandatory	-	-	(See Note 4)
	max	-	-	-	0.15	-		
Anti-oxidant, mg/l								
Hydrotreated Fuels	min	8.6 Mandatory	Optional	Optional	Optional	8.6 Mandatory		
	max	24		24	24	24		
Non Hydrotreated Fuels	max	24 Optional	Optional	24 Optional	24 Optional	24 Optional		
Metal Deactivator, mg/l	max	5.7 Optional	Optional	5.7 Optional	5.8 Optional	5.7 Optional		
Corrosion Inhibitor, mg/l (See Note 6)	max	By Agreement	By Agreement	By Agreement	Mandatory	By Agreement		
Anti-Static Additive (ASA-3), mg/l	max	1.0 By Agreement	1.0 By Agreement	1.0 By Agreement	Not Permitted	1.0 By Agreement		
Conductivity - at time/temperature of delivery to aircraft if ASA-3 present cu (pS/m)	min	50	50	50	-	50	274	D2624
	max	300	300	300	-	300		

NOTES: (1) ASTM D 2887 may be used as alternative in MIL-T-5624K only with following limits:- 20% vol at 130°C max; 50% vol at 185°C max; 90% vol at 250°C max; End Pt. 320°C max

(2) Alcor JFTOT method mandatory after 1/2/76

(3) Only for fuels treated by "copper sweetening" process.

(4) Method described in specification

(5) 70 min. if ASA-3 used.

(6) Details of approved Corrosion Inhibitors and concentrations can be obtained by reference to the specification concerned.

(7) Aviation Fuel Quality Requirements for Jointly Operated Systems

Table 3c

SUMMARY OF SPECIFICATION REQUIREMENTS FOR AVIATION GASOLINES

PROPERTIES		AVGAS SPECIFICATIONS									TEST METHODS	
		DERD 2475 Issue 1 March 1976	DERD 2485 Issue 7 Sept 1973		MIL-G-5572E Amendment 3 20th March 1975			ASTM D910-75			IP	ASTM
		Grade 100LL	Grade 100/130	Grade 115/145	Grade 80/87	Grade 100/130	Grade 115/145	Grade 80	Grade 100	Grade 100LL		
Colour (See Notes 1 and 2)		Blue	Green	Purple	Red	Green	Purple	Red	Green	Blue	17	D2392
Knock Ratings												
Lean Mixture - Motor Method	min	99 ON	99 ON	115 PN	-	-	-	-	-	-	236	D2700
or Aviation Method (see Note 3)	min	-	-	-	80 ON	100 ON	115 PN	80 ON	100 ON	100 ON	(236)	(D2700)
Rich Mixture	min	130 PN	130 PN	145 PN	87 ON	130 PN	145 PN	87 ON	130 PN	130 PN	119	D909
Tetraethyl Lead (TEL), ml/USG	max	(2.00)	(3.00)	(4.60)	0.50	3.00	4.60	0.50	3.00	2.00	96	D526
or as Lead (Pb), g Pb/l	max	0.56	0.85	1.28	0.14	0.85	1.29	0.14	0.85	0.56		
Aromatics, % vol.	min	5.0	-	5.0	-	5.0	5.0	-	-	-	156	D1319
Net Heat of Combustion, Btu/lb	min	18 700	18 700	18 900	18 700	18 700	18 900	18 720	18 720	18 720	12 or 193	D240 or D1405
or Aniline Gravity Product	min	7 500	7 500	9 000	7 500	7 500	9 800	-	-	-	2 and 160	D611 and D1298
Specific Gravity, 60°/60°F		Report	Report			-			-		160	D1298
or Gravity, API degrees		-	-			Report			-		-	D287
Distillation												
Initial Boiling Point, °C(°F)		Report	Report			-			-		123	D86
Fuel Evaporated, % vol. at												
75°C (167°F)	min	10	10			10			10		•	•
	max	40	40			40			40		•	•
105°C (221°F)	min	50	50			50			50		•	•
135°C (275°F)	min	90	90			90			90		•	•
End Point, °C (°F)	max	170(338)	170(338)			170(338)			170(338)		•	•
Sum of 10% plus 50% Fuel Evaporated Temperatures, °C (°F)	min	135(307)	135(307)			135(307)			135(307)		•	•
Residue, % vol.	max	1.5	1.5			1.5			1.5 (See Note 4)		•	•
Loss, % vol.	max	1.5	1.5			1.5			1.5		•	•
Freezing Point, °C (°F)	max	- 60(-76)	- 60(-76)			- 60(-76)			- 58(-72)		16	D2386
Reid Vapour Pressure, lb/in^2	min	5.5	5.5			5.5			-		69 or	(D323 or
	max	7.0	7.0			7.0			7.0		171	(D2551
Copper Corrosion, classification	max	1	1			1			1		154	D130
Sulphur, Total % wt.	max	0.05	0.05			0.05			0.05		107	D1266
Existent Gum, mg/100ml	max	3.0	3.0			3.0			-		131	D381
Oxidation Stability/Aging Gum 16 hours												
Potential Gum, mg/100ml	max	6.0	6.0			6.0			10.0) (See		138	D873
Precipitate, mg/100ml	max	2.0	2.0			2.0			4.0) (Note 5)		•	•
Water Reaction												
Interface Rating	max	2	2			2			-		289	D1094
Separation Rating	max	2	2			-			-		•	•
Volume Change, ml	max	2	2			2			2		•	•
Antioxidants (See Note 6), mg/l	max	24	24			24			24 (See Note 7)		-	-

NOTES: (1) Refer to specifications for full details of dye requirements.

(2) DERD 2475 & 2485 specify visual test with IP 17 (Lovibond) as reference method only.

(3) Aviation Ratings converted from Motor Method results.

(4) ASTM D910 requires that distillation residue is not acid by ASTM D1093.

(5) By agreement, this is acceptable alternative to 5 hour aging gum test required in ASTM D910.

(6) Refer to specifications for full details of permitted antioxidants.

(7) Applies only to fuel required to meet 16 hour aging gum test. Max. anti-oxidant content is 12mg/l for fuel tested by 5 hour aging gum method (See Note 5).

Table 4

Results of fast and pressure pyrolysis
(From Reference 12)

Type of carbonization	Southern African coals			NW Europe (Ruhr) coal			E Europe (Poland) coal		
	Slow	Fast (fluidized bed)	Pressure gasifier	Slow	Fast (solid/ solid or fluidized bed)	Pressure gasifier	High temp.	Slow	Fast (fluidized bed)
Oil/tar yield compared to assay	95-110	100-120	73	100	163	76	40	95	147
Oil/tars, SG	1.03	1.07	1.10	1.04	1.16		1.10	1.04	1.11
Composition of oil/tars, %v									
C_3-C_4	2.8	n.d.	7.8	3.1	5.0		10.8	7.0	2.8
C_5-200°C	24.8	45- 50	8.7	16.2	14.9		18.8	12.3	7.2
200-360°C	37.6		360	51.4	15.0			48.2	55.0
Vacuum oil	21.7	50- 55	47.5	14.8	24.1		71.4		
Vacuum residue	13.1			14.5	41.0			25.8	35.0
C_1 - vacuum oil % of Fischer	86	71	48	85	93	n.d.	20	62	95
Phenols, %v	25.0	n.d.	30.8	29.1			2	41.5	n.d.
Dust in heavy condensate, % mass	Low	High	19	Low	5- 10	High	Low	Low	5
C, % mass	84.0	n.d.	84.5	83.3	86.1		87.0	83.6	82.4
H, % mass	8.6		7.0	9.1	6.8		6.6	8.3	7.8
S, % mass	0.6		0.5	0.7	0.8		0.6	0.2	0.4
N, % mass	0.3		8.0	0.7	1.2		5.8		1.0
O, % mass	6.5			6.2	5.1			7.9	8.4
Distribution of hydrogen into oil (C_3 +)	29	30	21	21	30		7	21	27

Table 5

Jet fuel from coal tar fraction
(CERCHAR-1962)

Density, 20°C	0.886
Net heat of combustion, Btu/lb	18,330
Freezing point, °C	<-60
ASTM distillation, °C (max.)	
10%	195
20%	204
50%	228
90%	282
FBP	306
Flash point, °C (min.)	53
Total sulphur, %w	0.005
Total nitrogen, %w	<0.05
Hydrogen content, %w	12.7
H/C ratio	1.746
Saturated hydrocarbons, %w	89
Hydro-aromatic hydrocarbons, %w	11

Table 6

Percentage direct operating costs
International Operations
(From Reference 2)

	1973/4 Budget			1976/7 Forecast		
	Short haul	Long haul		Short haul	Long haul	
		747	707		747	707
Fuel	15	25	24	35	47	43
Maintenance	24	27	24	18	23	21
Standing charges	31	27	23	22	12	12
Crew	18	10	20	15	10	16
Land & navigation charges	12	11	9	10	8	8

Table 7

The costs of alternative energy

	1976 US dollars per barrel oil equivalent
1. Thermal energy	
Indigenous coal (USA)	4- 5
Imported coal (NW Europe)	6- 10
Indigenous coal (NW Europe)	8- 15
Nuclear input break-even value (the fuel input cost required for fossil-fuelled plants to produce electricity at the same cost as nuclear stations)	5- 10
Low Btu gas from indigenous coal (USA)	10- 15
LNG (liquefied natural gas - high Btu) imports (Europe, Japan, USA)	10- 20+
SNG (synthetic natural gas - high Btu) from indigenous coal (USA)	20- 30+
Liquids from coal, oil sands or shale (N America)	15- 25
Liquids from imported coal (NW Europe)	25- 35
Biomass (crops grown for fuel)	40- 50
Solar hot water (on site, 35° latitude)	40+
2. Electricity output	
Based on conventional thermal and nuclear generation (at power station)	40- 70
Based on wind (1985 estimate, on site)	50+
Based on photovoltaic solar (1985 estimate, on site)	120+

The costs (not prices) shown above are all expressed in terms of a standard energy unit (one barrel of oil equivalent, equal to 5.8 million British thermal units), but their outputs vary, not only in form (heat or electricity), but also in terms of quality, location and availability. The figures above exclude refining, storage, transmission or distribution costs and various other factors that enter into the decision process on energy choice. The costs shown can also change considerably over time as a reflection of, for example, the differential inflation often affecting new complex technological processes or the potential learning curve effect involved with processes that are at present still in the research or pilot stage.

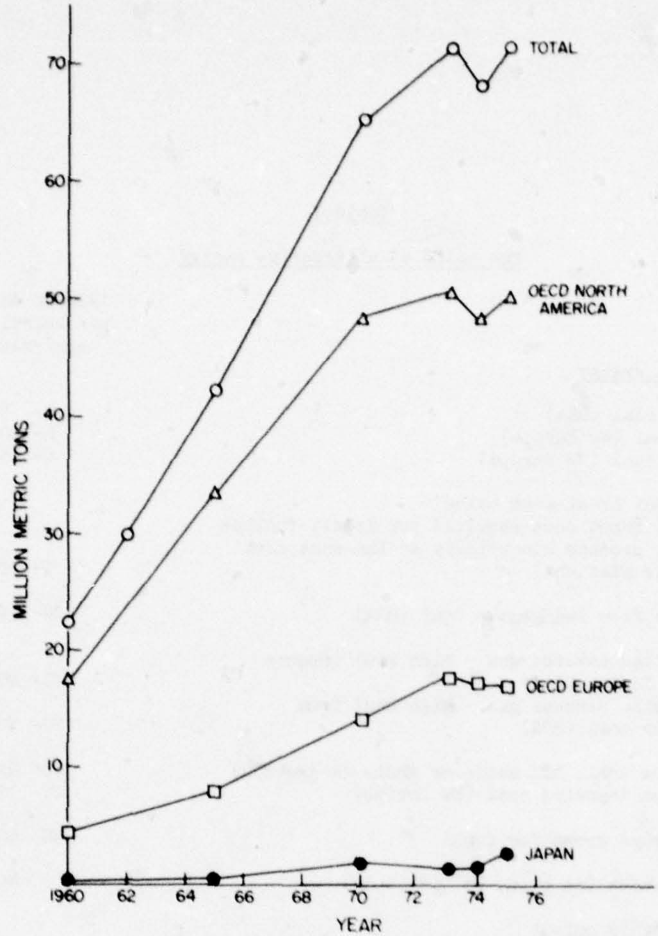

FIG 1-Consumption of aviation fuels 1960-75

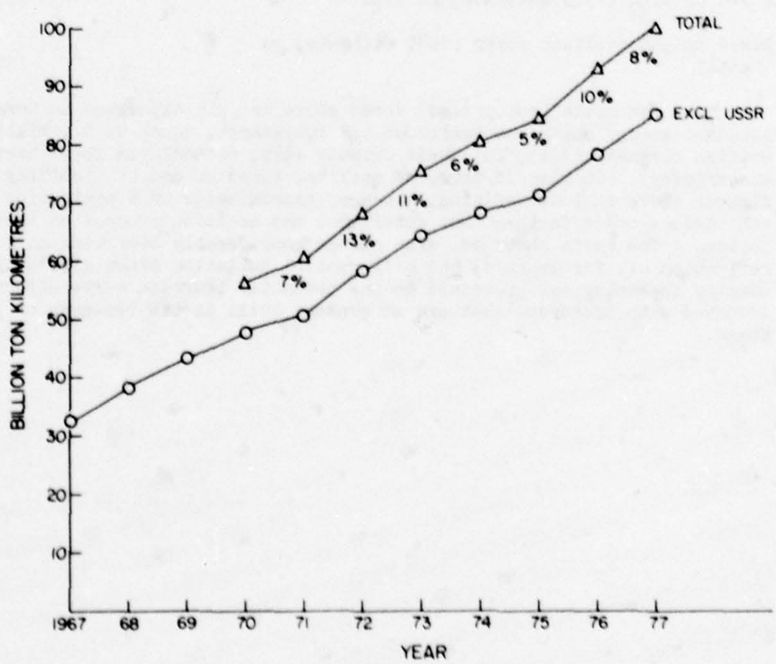

FIG 2 - World scheduled revenue traffic - Total services - Passengers + baggage + freight + mail (Reference 3)

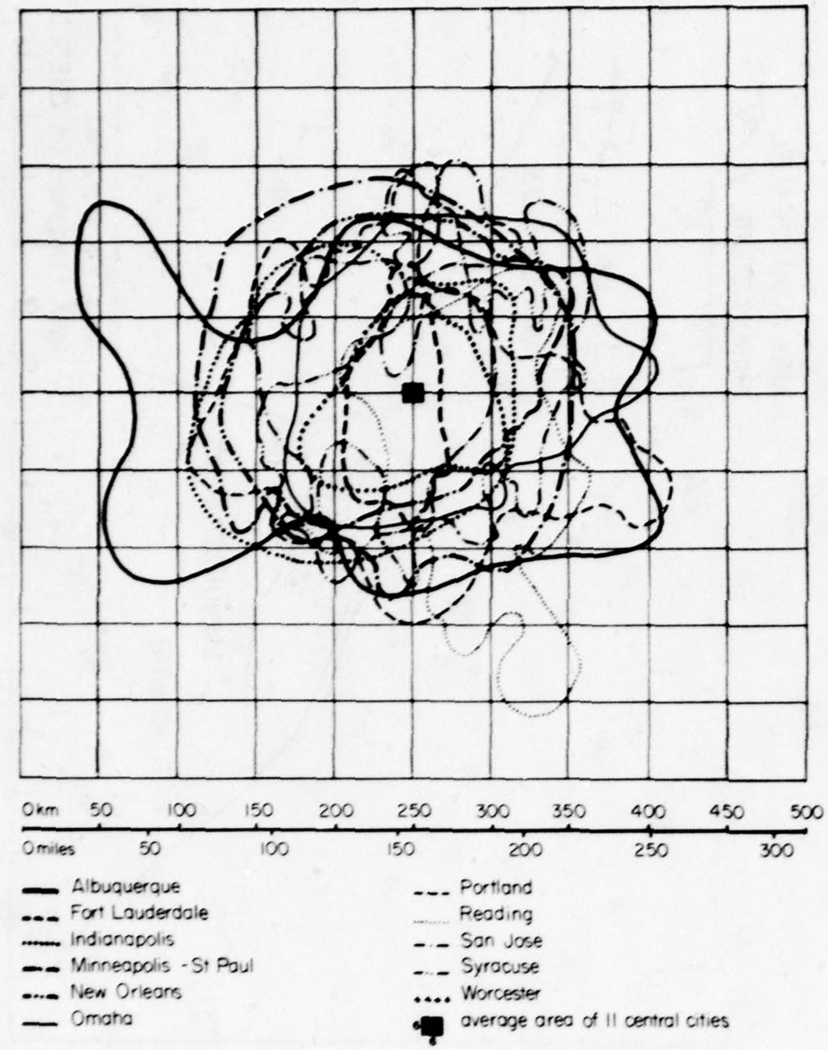

FIG 3 — Commuting fields of 11 American cities in 1960
(from Reference 4)

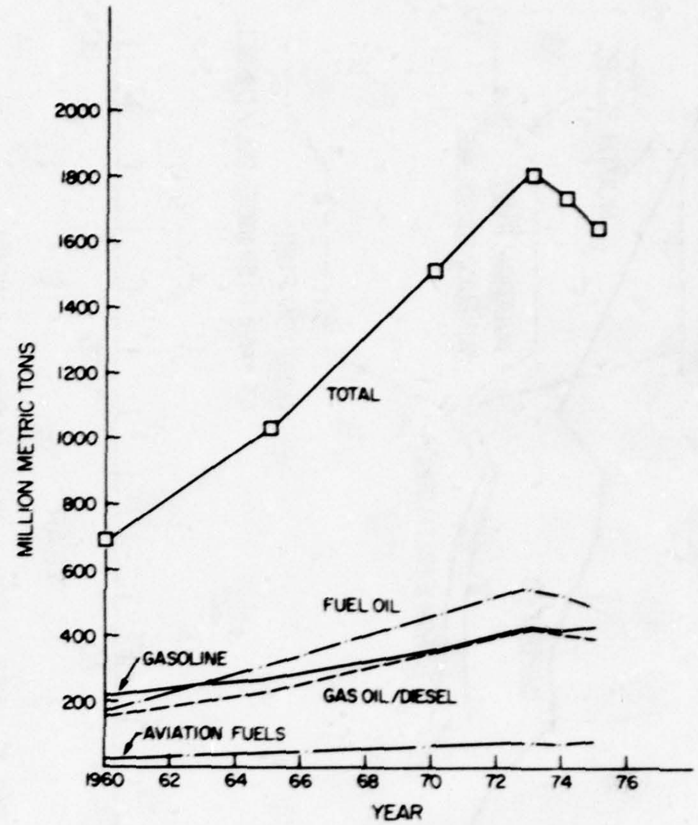

FIG 4 - Consumption of main products 1960 - 75 -
OECD area total

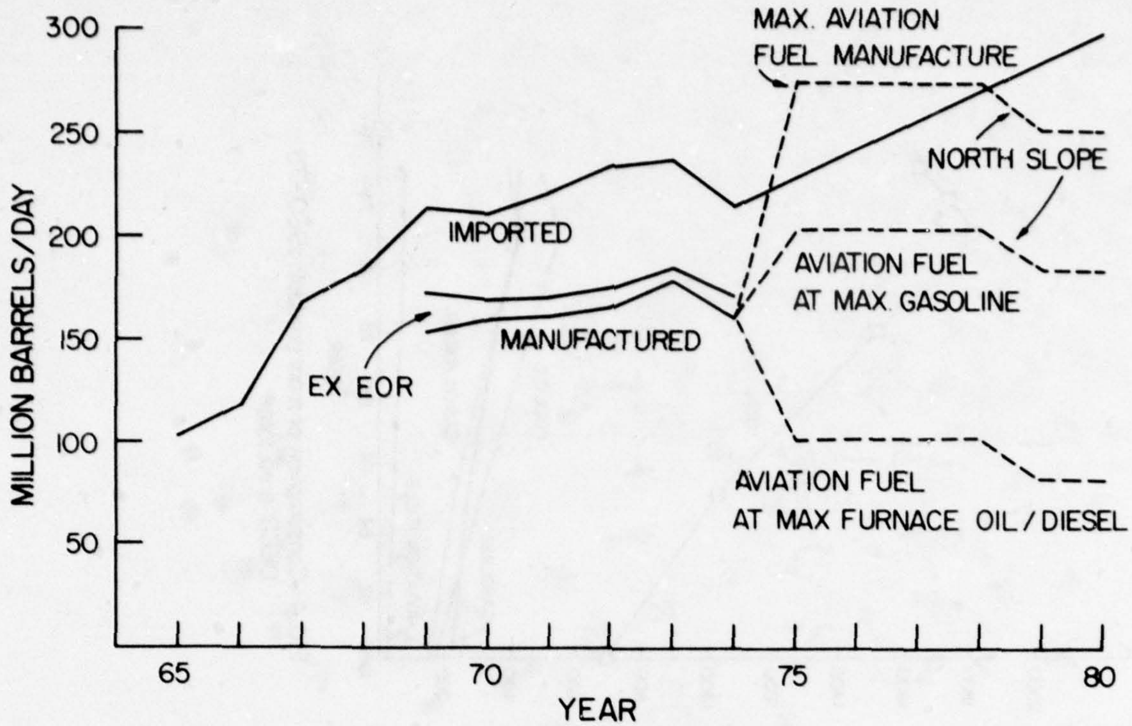

FIG. 5 — ATF supply — West of Rockies (WOR)

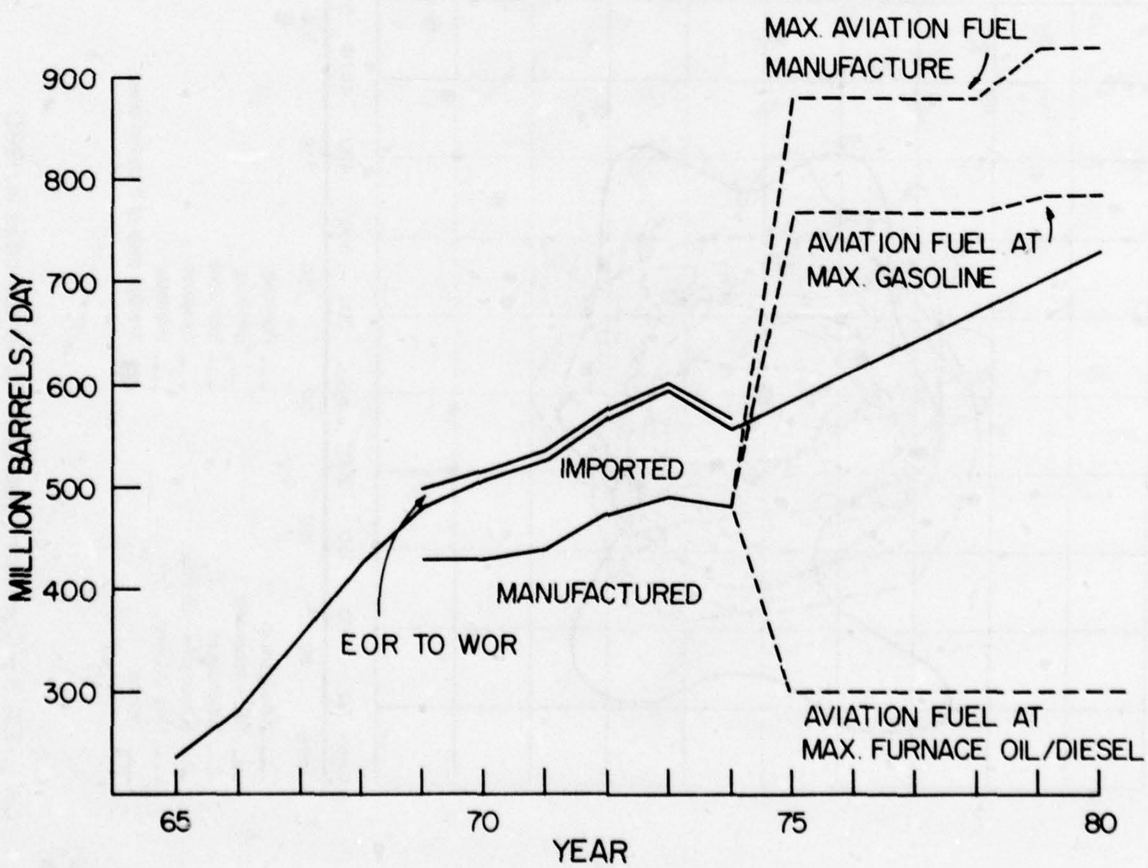

FIG. 6 — ATF supply — East of Rockies (EOR)

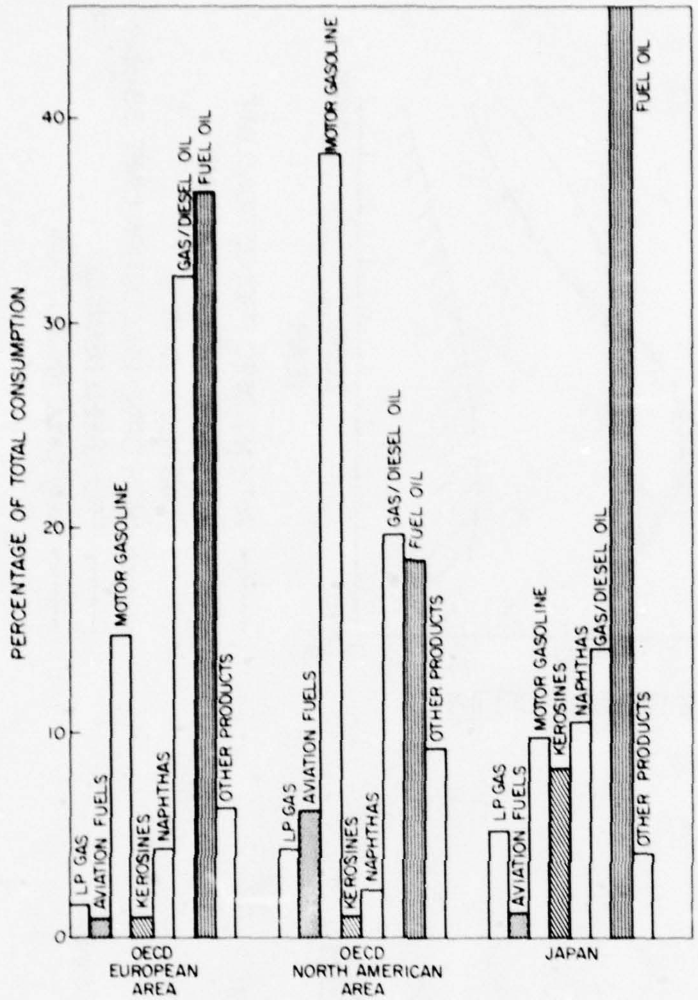

FIG. 7a – Consumption of products – OECD areas – 1975

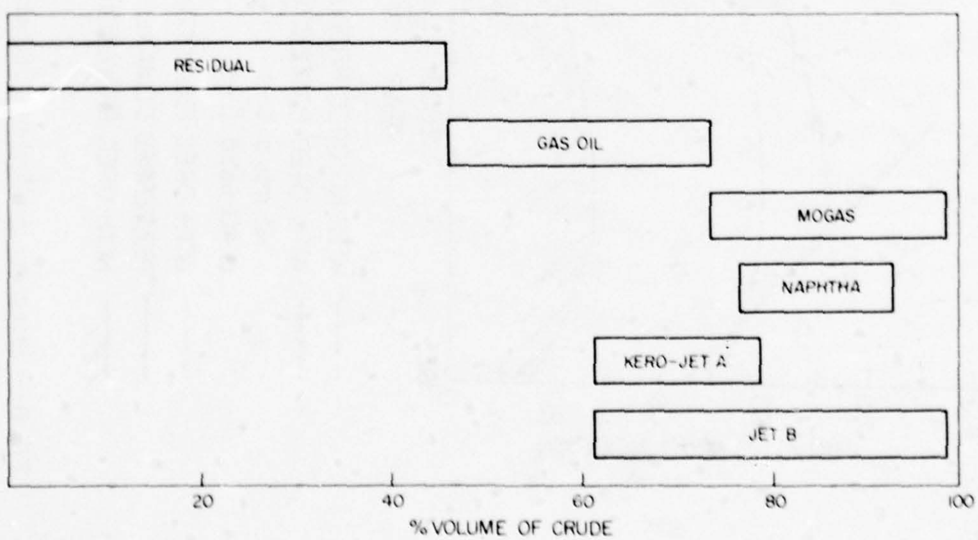

FIG. 7b – Straight run yield from average Persian Gulf crude oil

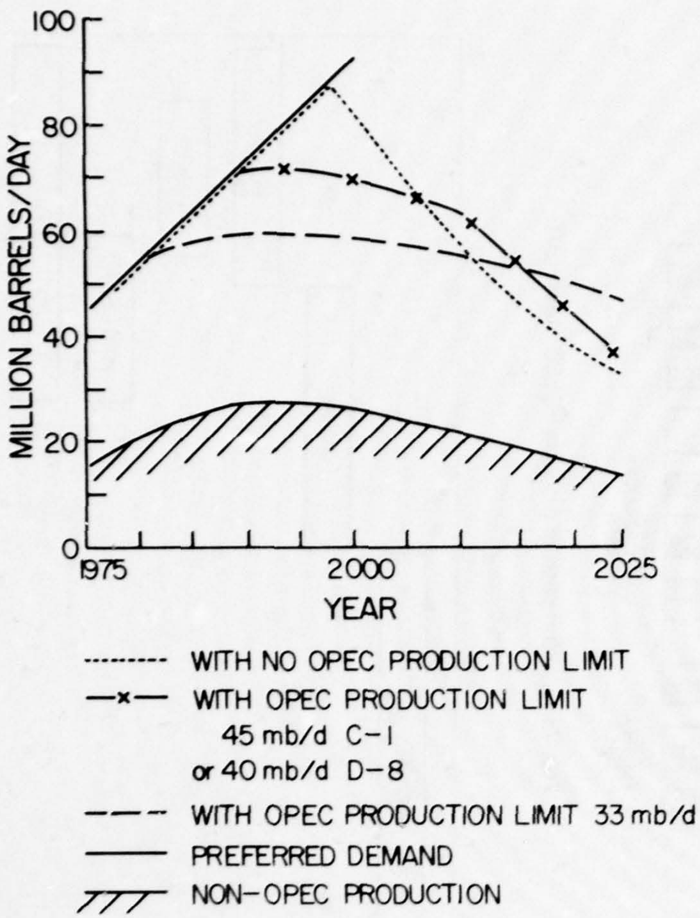

FIG. 8 — World oil production: Scenario C1 — High growth, rising energy price, vigorous policy throughout (additions to reserves: 20 billion barrels per year)

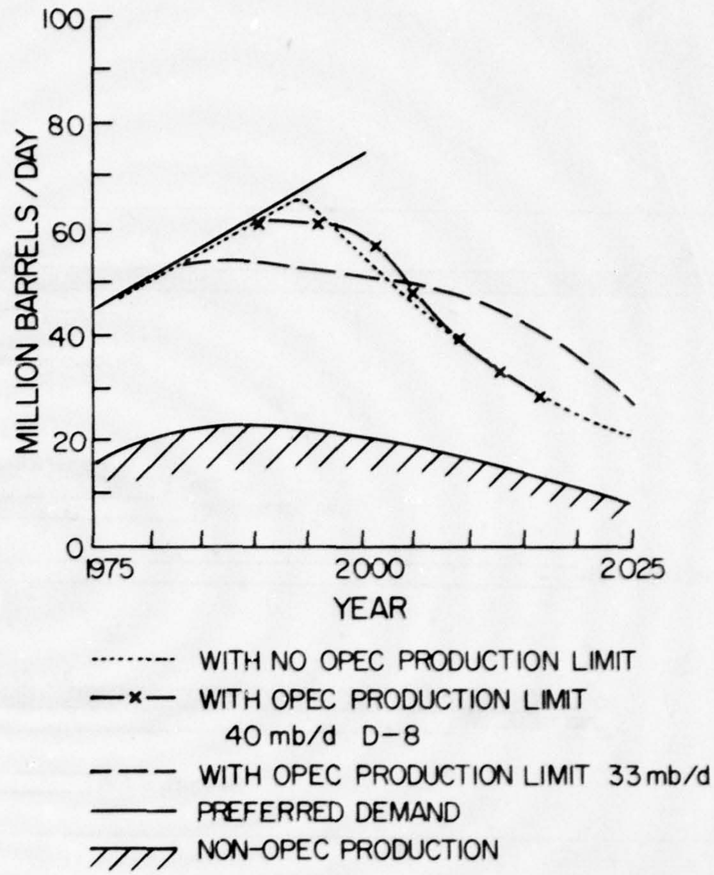

FIG. 9 — World oil production: Scenario D8 — Low growth, constant energy price, policy restrained until 1985 (additions to reserves: 10 billion barrels per year)

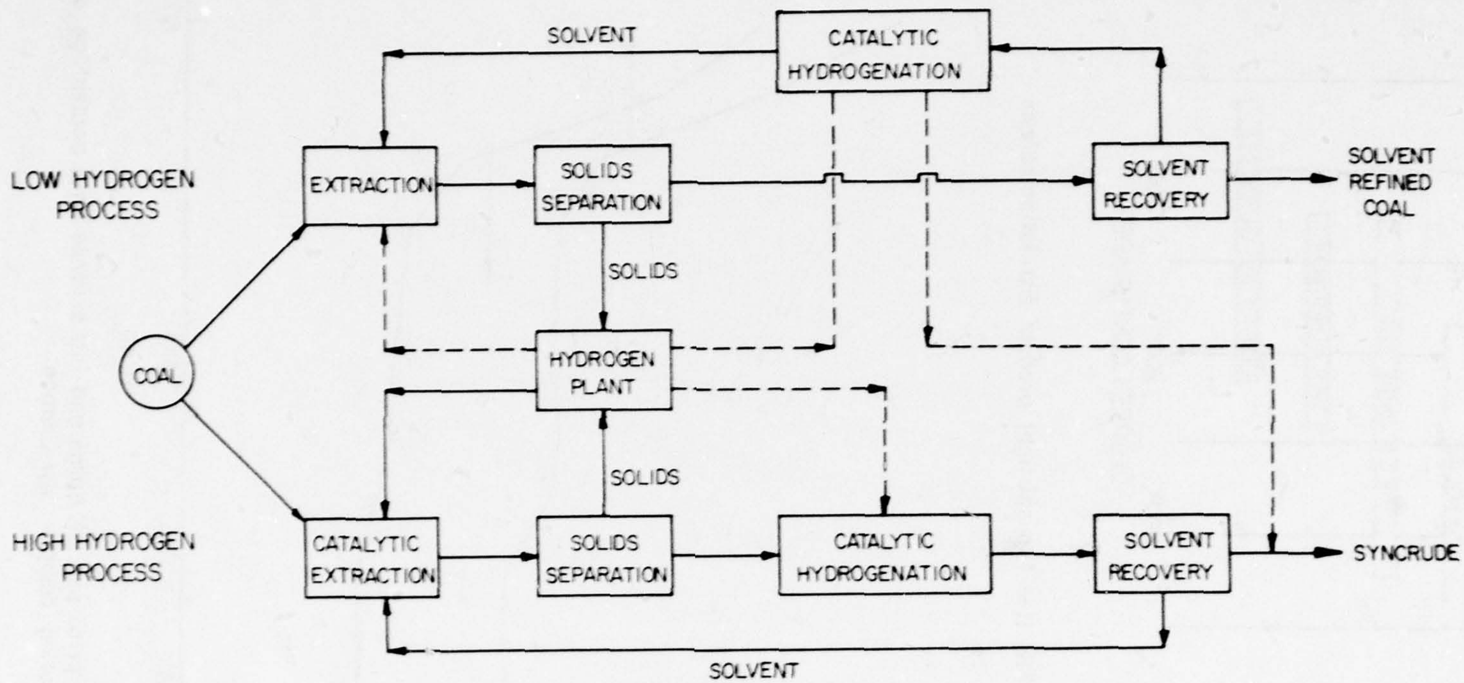

FIG. 10 — Generalized flowsheet for coal liquefication

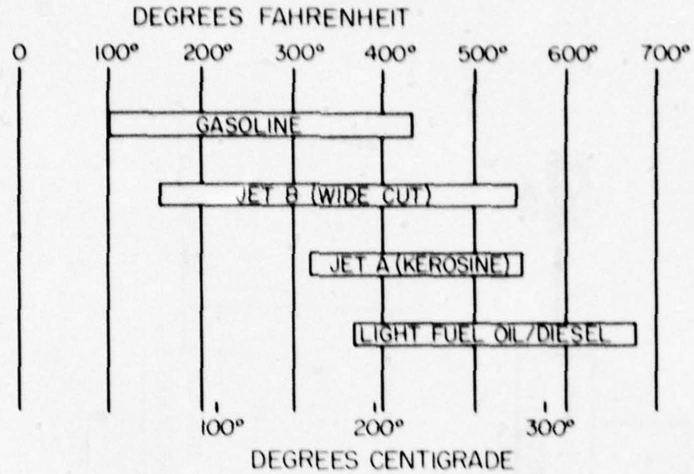

FIG. 11 — Typical light product distillation ranges

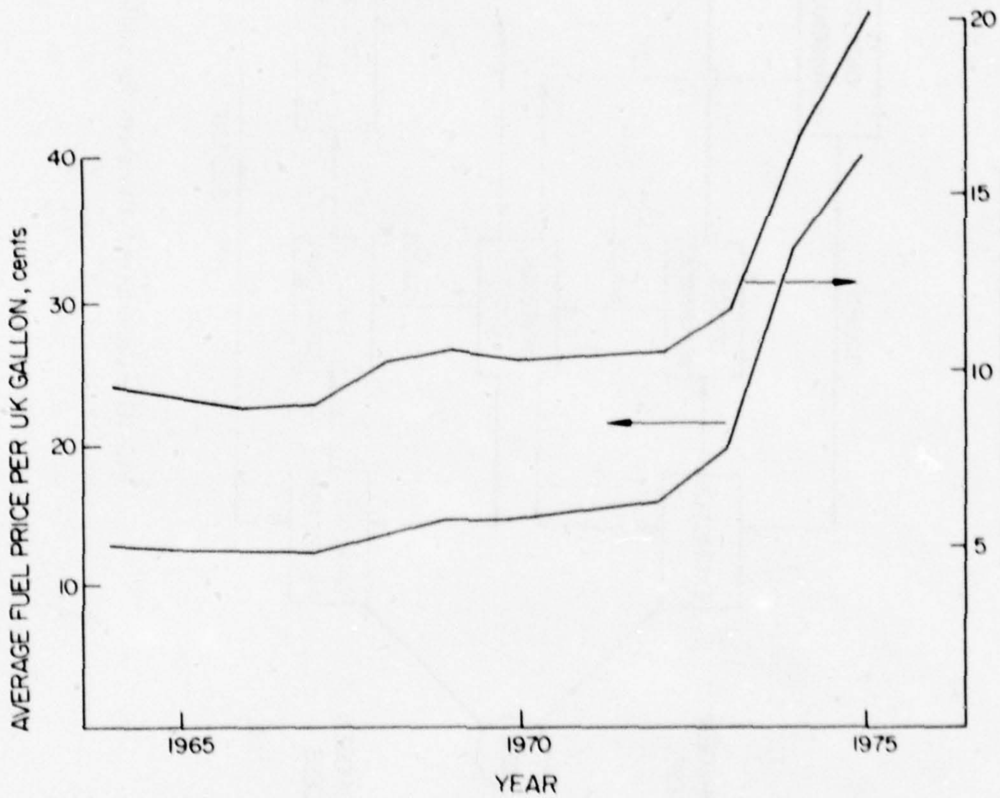

FIG. 12 — Fuel price per UK gallon and fuel expense as a percentage of total operating costs — Air Canada

THE ROLE OF FUNDAMENTAL COMBUSTION RESEARCH IN THE FUTURE AVIATION FUELS PROGRAM

by

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1. PREVIOUS ALTERNATIVE FUELS RESEARCH IN THE OLDER CAN TYPE ENGINE COMBUSTORS

A study made recently of the composition of fuels delivered under the Avtur 40 and Avtur 50 specifications (Jet A and Jet A1) in the United Kingdom shows that over the 25 years or so of their joint existence, the aromatics content was held in range 8 to 15% (well below the specification limit of 20%) until very recently. This period has seen the development of the gas turbine from maximum operating pressures of a modest 5 or 6 bars to values currently approaching 30 bars, with a corresponding increase in combustor inlet temperature (now about 900°K). The tendency in empirical development of combustors towards rich primary zones was discussed in section 5 of the previous lecture. Carbon formation in the primary zones of the earlier can-type combustors proved to be very sensitive to aromatics content, small increases above 20% causing almost exponential increase in carbon deposit formation and this situation can be expected to be aggravated by the engine design changes which have taken place since.

The major part of the information whicn has been obtained as the result of these twenty-five years or so of empirical combustor development is in the form of the overall response of the system to fairly arbitrary changes in fuel properties and fuel preparation. The quantities observed are such things as carbon deposit formation, wall temperature, combustor outlet temperature distribution, combustion efficiency etc. This information,being peculiar to the particular individual combustor design on which the measurements were made, is (a) treated as company confidential "know-how" and given only very limited publication and (b) is very difficult to generalize into a basic understanding of the effects of the various fuel and combustion parameters on detailed flame behaviour. Measurements of fuel/air ratio distribution profiles in the primary zone are usually completely lacking. The necessary techniques of primary zone products sampling and on-line fuel/air ratio measurement by chemical analysis have only become available as a routine development tool in the last five years or so (20). Fast on-line primary zone combustion efficiency measurement by detailed gas analysis (21, 22) is still in the research laboratory stage. Gas velocity distribution measurements which can give an understanding of mass flow rate distribution and flow pattern are also still only a research laboratory tool.

2. RESEARCH USING EXPERIMENTAL MODEL COMBUSTORS

To avoid the difficulties inherent in using full scale engine type combustors for flame research to throw some light on the way in which carbon is formed in gas turbine primary zones, a research program was undertaken (23, 24) in small laboratory flames in which the combustion parameters could be controlled and their effects isolated in various ways.

The first experimental system (23) was aimed at eliminating droplets from the combustion altogether, the fuels being fully pre-vapourized and premixed with the combustion air before injection into the combustion space. A spectrum of eight different C_5 and C_6 hydrocarbons ranging from n-pentane through to benzene was chosen to study the effects of a wide range of fuel carbon/hydrogen ratios. The burner system, Figure 1, was required to operate at pressures up to 20 bars and over a range of equivalence ratios from the normal weak limit for hydrocarbon/air flames ($\phi \approx 0.45$) up to the rich limit ($\phi = 2+$). The quenching diameter for hydrocarbon/air flames is extremely small at the top end of this pressure range (for paraffin hydrocarbons, 0.15 mm at 20 bars). A bundle of such burner tubes was therefore formed into a small cylindrical multihole flat flame burner (12 mm diameter), rather like a small Meker burner.

For each hydrocarbon, quantitative measurements were made of soot formation and general flame composition over a range of equivalence ratios at several pressure levels up to 20 bars. The data were then crossplotted to produce a set of soot formation rate contours as a function of pressure and equivalence ratio of the kind shown in figure 2. The word soot is used here, rather than carbon. It was observed that beyond a threshold equivalence ratio which was about half the theoretical equivalence ratio for carbon formation in chemical equilibrium, unburnt hydrocarbon was produced in the flames. Depending on the duration and level of thermal stress to which it was exposed, this hydrocarbon underwent a varying degree of thermal breakdown. Conditions close to the soot formation threshold equivalence ratio, with high flame temperatures, produced dry amorphous carbon. At a given pressure condition, particularly in the lower part of the pressure range, as the flame was made richer, there were increasing amounts of benzene-soluble tar mixed with the carbon until, at very rich mixtures, the material was entirely benzene-soluble. The dependence of the degree of carbonization on flame temperature was further demonstrated by increasing the flame temperature for a particular set of combustion conditions (a) by reducing heat loss from the flame by increasing the reflectivity and insulation of the confining wall and (b) by changing the diluent gas from nitrogen to argon (which has a smaller heat capacity than nitrogen).

The linear relationship between the fraction of the original carbon in the fuel appearing as solid carbon in the flame, and the carbon/hydrogen ratio of the fuel is shown in Figure 3 (taken from 24). The values plotted were all measured at a pressure of 15 bars and equivalence ratio = 2.

For experiments with aviation kerosine, a 75 mm diameter cylindrical model combustor was designed. It had a flat baseplate with an annular jet concentric with the cylindrical confining wall and only a few mm from it. From this, the whole of the primary air, was fed as a continuous annular film, close to the combustor wall. Gases from the centre of the flame were entrained on the internal surface of the jet

and a tight stable torroidal flow reversal system was produced. Kerosine was either prevaporized and premixed with the air upstream of the discharge plane of the annular jet or was fed as a circumferentially uniform flat sheet of spray from a rotary atomizer placed in the centre of the base plate. For some later work, a bifluid acoustic atomizer which also produced a flat concentric sheet of spray was also used (Fig. 4). Under good operating conditions, the flame produced by this flow system was of substantially uniform composition and flame products were sampled by means of a multihole cruciform gas sampler placed at a plane one diameter downstream of the base plate. The combustor was operated over the same range of pressures and equivalence ratios used with the earlier premixed burner and the premixed kerosine/air flames showed very similar behaviour to the earlier small scale flames (Fig. 5).

Tests burning atomized kerosine (25) showed much heavier carbon-formation at weaker mixtures than the threshold mixture strength for carbon formation for premixed kerosine/air flames (threshold $\phi = 1.2$) and, at the highest pressures tested, carbon formation extended well on the weak side of stoichiometric (to $\phi = 0.8$) (Fig. 6).

3. THE MECHANISM OF CARBON FORMATION IN SPRAY FLAMES

Droplets of kerosine in a flame should evaporate at a liquid temperature at or near the boiling point temperature appropriate to the ambient pressure. Edmister (26), on the basis of experimental measurements of the equilibrium flash distillation curves over a range of pressures up to the critical pressure, for gasolines, kerosines and distillate fuel oils from several sources has devised an empirical correlation of the data, which permits the construction of the phase diagram for such a fuel given that the ASTM distillation curve, or the true boiling distillation curve is known. For a typical aviation kerosine this method gives a critical temperature of about 400°C, at a critical pressure of 23.5 bars. There is no reason why a kerosine droplet should become superheated so 400°C represents the upper limit temperature for evaporation from the liquid phase. This temperature is well below the threshold for thermal cracking of such hydrocarbons, even for residence times of several seconds (27). Similar calculations for a gas oil (a Reference Fuel B310 in use at one time in the U.K.) gives a critical temperature of 473°C (Critical Pressure 23 bars). This is still on the low side for liquid phase cracking which, according to (27) has a threshold temperature of about 550°C.

The marked effect of pressure apparent in Figure 6 in increasing the degree of carbon-formation suggests a mechanism similar to the one operating in fully premixed flames and dependent on small scale spatial variations of mixture strength in the flame as a consequence of poor mixing of air and fuel vapour from the evaporated droplets in the pre-flame region, due to low turbulence levels. It is also possible that ordered time-wise fluctuations of mixture strength might occur at a characteristic frequency, controlled by vortex shedding from the air jet system used in stabilising the primary flame. Time-resolved measurements of flame properties would be required for studying this possibility. For the velocities encountered in gas turbine combustion, such techniques have just not been developed.

4. FUTURE RESEARCH USING MODEL COMBUSTORS

The work described in (23, 24, 25) has permitted some observations to be made on the problems of rich flame chemistry at high pressure. The extension of this type of technique, with a better understanding of the fluid dynamic effects, could make a timely contribution to the alternative aviation fuels program if applied to a range of fuel types. Such a research program would be very demanding in the facilities required and in particular, would stretch observation techniques to the limit.

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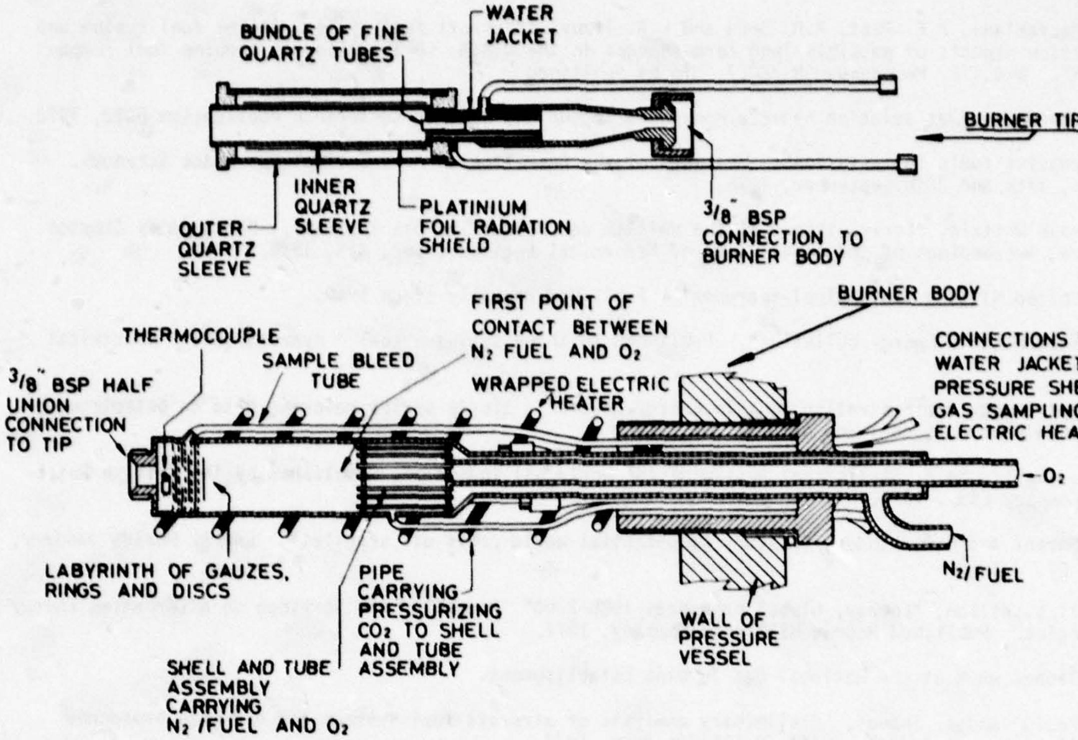

Fig.1 Flat flame burner

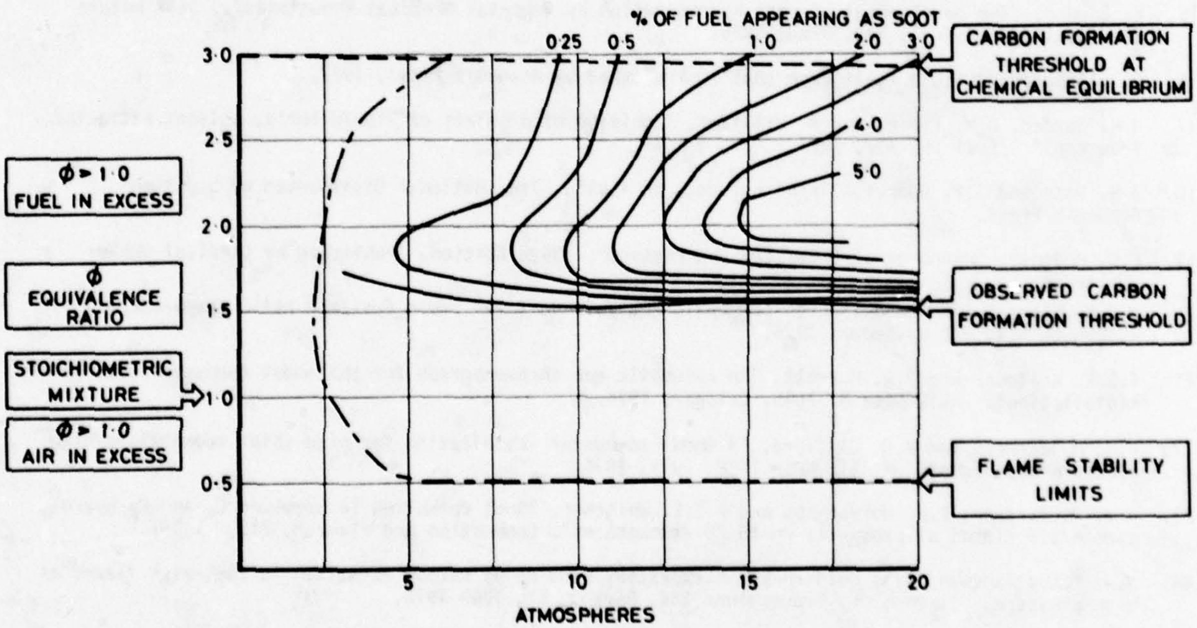

Fig.2 Soot formation contour map for premixed cyclohexane/air flames

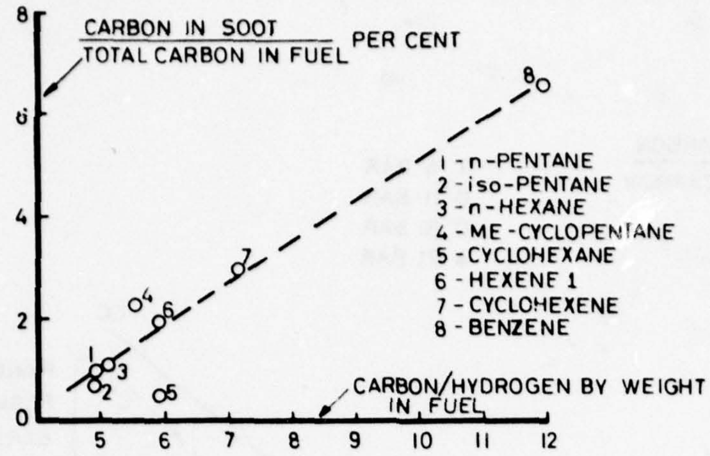

Fig.3 Soot formation versus carbon/hydrogen ratio of the fuel, for premixed flames

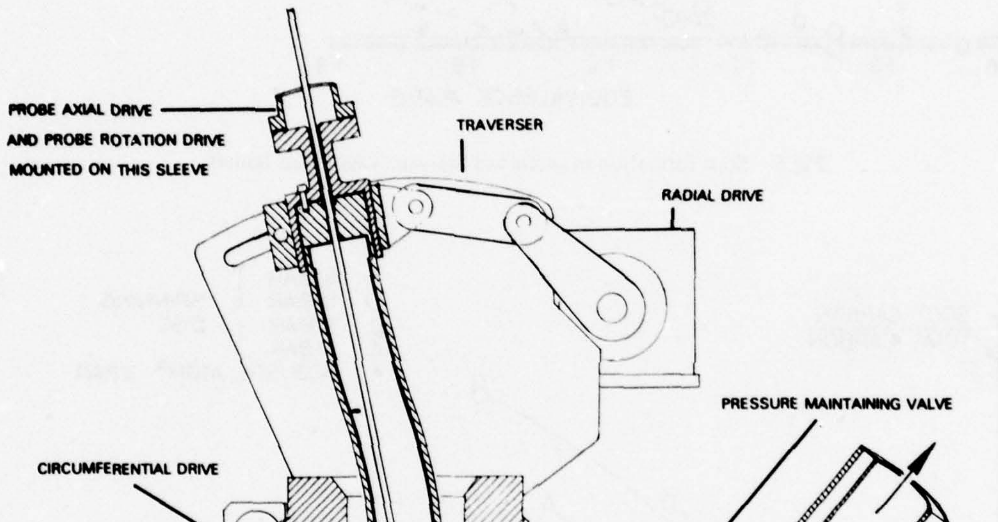

Fig.4 The model combustor

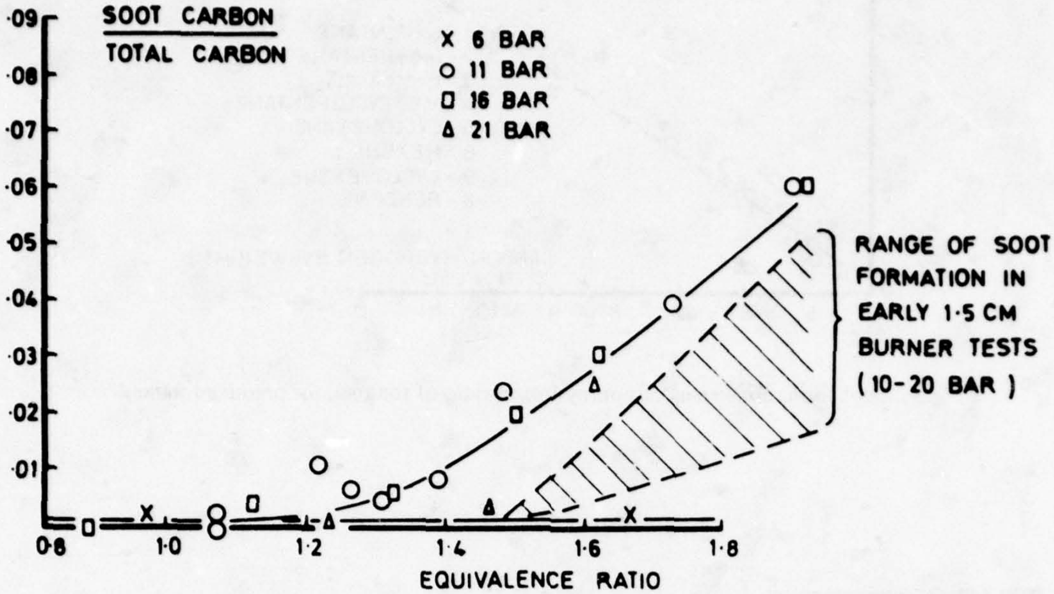

Fig.5 Soot formation in premixed kerosine vapour/air flames

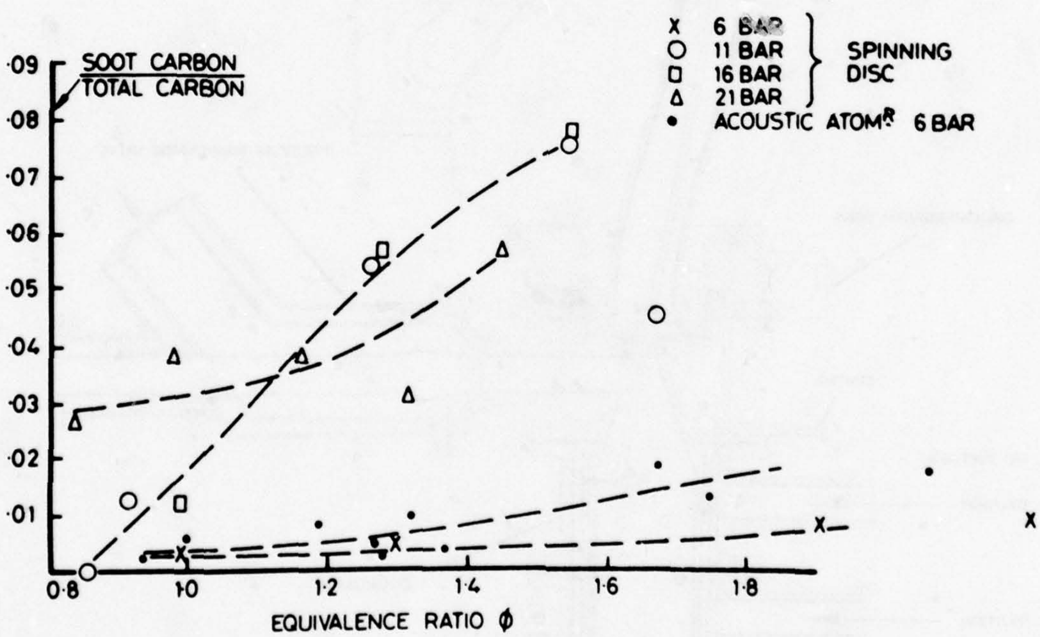

Fig.6 Soot formation in kerosine spray flames

CHARACTERISTICS AND COMBUSTION OF FUTURE HYDROCARBON FUELS

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SUMMARY

As the world supply of petroleum crude oil is being depleted, the supply of high-quality crude is also dwindling. This dwindling supply is beginning to manifest itself in the form of crude oils containing higher percentages of aromatic compounds, sulphur, nitrogen, and trace constituents. The result of this trend is described and the change in important crude oil characteristics, as related to aircraft fuels, is discussed. As available petroleum is further depleted, the use of synthetic crude oils (i.e., those derived from coal and oil shale) may be required. The principal properties of these "syncrudes" and the fuels that can be derived from them are described and discussed. In addition to the changes in the supply of crude oil, increasing competition for middle-distillate fuels may require that specifications be "broadened" in future fuels. The impact that the resultant potential changes in fuel properties may have on combustion and thermal stability characteristics is illustrated and discussed in terms ignition, soot formation, carbon deposition, flame radiation, and emissions.

INTRODUCTION

This paper describes some of the changes in fuel properties that may be expected in future hydrocarbon fuels for aircraft and discusses the effect that these property changes may have on selected combustion and thermal stability characteristics relevant to aircraft jet engines. Many studies are currently under way within the United States to predict the future availability and characteristics of crude oils (1-4). Included in many of these studies is an analysis of the processing required to upgrade low-quality feedstocks, such as crude oils derived from oil shale and coal, to the current specifications for jet aircraft fuels. Severe economic and energy consumption penalties will likely occur if these low-quality crudes must be refined to current specifications. Similarly, converting high-boiling petroleum fractions to current-specification jet fuel, which may be necessary because of a shortened supply of middle distillates, requires energy-intensive hydroprocessing (5). An alternative would be to relax fuel specifications and thereby minimize the economic and energy consumption penalties. However, the relaxed-fuel-specification approach would require the development of a new level of engine and aircraft fuel-system technology (6).

An assessment of the main advantages and disadvantages of these two approaches is shown in Figure 1. The continued production of current-specification jet fuel certainly is the best approach from the aircraft airframe and engine manufacturers' point of view. But, as already mentioned, it may be prohibitive from an economic and refining-energy-consumption point of view. Relaxing the current jet-fuel specifications would obviously minimize the energy consumption and economic penalties but may be prohibitive because it may require more complex component technology and may adversely affect engine life.

The solution to projected fuel availability problems will most likely be to relax the fuel specifications to a point governed by a trade-off between the fuel cost and refinery energy consumption and the cost and development difficulty of new technology for engines and aircraft fuel systems. Developing the data base needed to make this trade-off is the primary objective of the Fuels Technology Program being conducted by the National Aeronautics and Space Administration (NASA). Much of the information presented in this paper is derived from this program. Other U.S. Government and aircraft-industry-sponsored programs also provided information to this paper.

Illustrations are used to describe the changes in jet aircraft fuel properties that will most probably occur if fuel specifications are relaxed. The effect of these properties on certain combustion characteristics is also illustrated, and possible variations in fuel thermal stability are described. This is the first part of a two-part lecture on the characteristics of possible alternative hydrocarbon fuels and their effects on future jet aircraft. Reference 7 is the second part of the lecture.

CHARACTERISTICS OF JET-FUEL FEEDSTOCKS

Petroleum Crude Oil

The compositions of some typical petroleum crude oils from various sources are shown in Table I (taken from ref. 8). Selected data are included in Table I for both the total crude and several middle-distillate fractions from which jet and diesel fuels are produced. The sulfur content of petroleum obtained from different sources varies considerably. The variability of the hydrogen content is significant in that many of the currently important sources of petroleum, such as the Alaskan crude from Prudhoe Bay, tend to have a relatively high aromatic content. The nitrogen content of petroleum is gen-

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erally quite low. The higher-boiling range fractions contain relatively more sulfur and nitrogen and less hydrogen (a lower hydrogen-carbon ratio, thus a higher aromatic content) than the lower-boiling-range fractions.

Synthetic Crude Oils

A similar set of data for "synthetic" crude oils derived from oil shale and coal are shown in Table II (taken from ref. 8). The sulfur, nitrogen, and hydrogen contents of the shale-derived crude oils are reasonably comparable with one another regardless of the process used to extract the oil from the shale. The sulfur, nitrogen, and hydrogen contents of the coal-derived syncrude produced by the Synthoil process were all lower than those of the shale oils. The higher-boiling-range fractions in the shale oils contain considerably more nitrogen, in the form of organic nitrogen compounds, than do the lower-boiling-range fractions. The hydrogen content for both the shale oils and coal syncrude is reduced significantly as the boiling range is increased. The low hydrogen content of the middle-distillate fractions in the coal syncrude is particularly significant because of the corresponding high aromatic content. (The composition of the Synthoil fractions can vary considerably depending on the properties of the coal feedstock used and the process operating conditions, including the degree of hydrogenation.) In addition, other processes such as H-coal (9) would produce an oil with somewhat different properties from the same Kentucky coal feedstock.

Comparison of Selected Key Properties

Two of the key crude-oil properties that have an important effect on jet-fuel characteristics are compared in Figures 2 and 3 for various crude-oil feedstocks. Figure 2 compares the hydrogen content by weight percent of petroleum crude, shale oil, and coal syncrudes derived from a variety of sources and processes. The variation in shale-oil hydrogen content is minimal, but the variation in petroleum-crude hydrogen content is rather large, with the lower end nearly at the same level as the shale oil and coal syncrude. This factor is important because the need to upgrade low-quality petroleum crudes to the same extent as the shale oil and coal syncrude may impose an economic penalty on refining current-specification jet fuel long before any of the "synthetic" crude oils are available. As mentioned earlier, the hydrogen content of coal syncrudes may vary considerably beyond that shown in the figure, depending on the amount of hydrogen added to the coal, which has a hydrogen content of about 4 to 5 percent. Figure 3 compares the nitrogen content by weight percent of the various crude-oil feedstocks. For this property, both the variation and the level in petroleum crude are minimal, but both the variation and the level in shale oil are very significant. These characteristics imply that upgrading of the crude to reduce nitrogen content in jet fuels probably will not be needed until shale-oil feedstocks become available.

The importance of the hydrogen and nitrogen levels in fuels is discussed in detail in the section FUEL PROPERTY EFFECTS and THERMAL STABILITY.

CHARACTERISTICS OF JET FUELS

Current-Specification Fuels

Some of the key characteristics of aircraft hydrocarbon jet fuels are shown in Table III, along with their effect or relevance in aircraft propulsion systems. The American Society for Testing Materials (ASTM) specifications for jet fuels, including Jet B, Jet A and Jet A-1, are shown in Table IV. The average properties for a current Jet A fuel are also shown in Table IV for comparison. In general, the average property values for Jet A fuel fall well within the required maximum or minimum specification limits. Many of these characteristics are interrelated and can vary considerably with changing base-point conditions. For example, the variation in heat of combustion with specific gravity is illustrated in Figure 4. A significant decrease in heat of combustion by weight occurs as specific gravity (density) is increased over the range allowable in the specification. This decrease is somewhat compensated for by the increase in the heat of combustion by volume that occurs simultaneously. Since aircraft fuel systems are volume limited and the aircraft themselves are often weight limited, there are no significant range or performance penalties as long as the specific gravity remains within the specified limits.

The boiling range of jet fuels can vary from about 60° C for Jet B to about 270° C for Jet A. The boiling ranges of these fuels and two other petroleum products are shown in Figure 5. The boiling range of Jet B fuel (JP-4) is directly comparable to the boiling range of gasoline (also naptha for petrochemicals) at the low ends and to the boiling range of Jet A (JP-5), no. 2 diesel oil, and home heating oil at the high end. The boiling range of Jet A fuel is primarily comparable to the high-boiling-range no. 2 diesel and home heating oils. This overlap of boiling ranges can have a significant impact on the specification values if they have to be relaxed to improve jet-fuel availability. Complete distillation curves for some fuels are presented in Figure 6. Jet A and Jet A-1 fuels are less volatile than Jet B and Avgas, as clearly illustrated on this figure by the

much higher initial boiling point (0 percent evaporated).

Another measure of fuel volatility is the vapor pressure characteristics shown in Figure 7. The initial boiling point of jet fuels is determined by the allowable limits for flashpoint (Jet A) or Reid vapor pressure (Jet B) shown in Table IV. The fuel volatility must be low enough to prevent the formation of flammable vapors at ambient conditions. Jet A is currently endorsed for commercial aircraft because of its lower probability of fire during emergency landings (10). Although low volatility is desirable for safety, it adversely affects the ignition and altitude relight capabilities of the fuel.

Another fuel property that is important in determining fuel ignition characteristics is fuel viscosity. The variation of viscosity as a function of fuel temperature is shown in Figure 8. The less volatile fuels are more likely to encounter ignition difficulties because of their higher viscosities. As with vapor pressure, the variation of viscosity with temperature is an exponential effect and becomes much more severe as temperature is reduced.

This discussion does not include all the characteristics of current-specification fuels. It was intended only to point out some selected key fuel characteristics and to describe how they vary within the listed specification limits.

Projected Changes in Fuel Properties

Perhaps one of the most significant trends in fuel properties over the last 15 years has been the steady increase in the average aromatic content of commercial Jet A fuel. This trend is illustrated in Figure 9, where it is compared with the current ASTM Jet A specification limit. During the emergency period 1973-74, limited quantities of highly aromatic jet fuels were used as illustrated in Figure 9 by the 22-percent aromatic content of Jet A refined from a heavy Arabian crude. An estimate for Jet A refined from Alaskan crude indicates that aromatic content may be as high as 25 percent. Because of these recent trends, a waiver limit of 25-percent aromatic content has been set by the ASTM for Jet A fuel. The higher-aromatic-content petroleum crude sources may require additional hydroprocessing at the refinery to reduce the aromatic content to current specifications. Furthermore, future shortages of middle distillates may ncessitate the conversion of higher-boiling-range petroleum cuts to middle-distillate fractions (5). These "cracked" fuels would have higher aromatic content and thus would require additional hydroprocessing to meet current specifications. A very simplified schematic of the type of processing required is shown in Figure 10.

Hydroprocessing techniques to improve fuel quality in terms of hydrogen and nitrogen content will also be needed if fuels refined from syncrude feedstocks must meet current specifications. The amount of hydrogen that would be consumed to raise a coal-syncrude hydrogen content from 12.5 percent to 13.5 percent would be 100 cubic meters per cubic meter of oil, as illustrated in Figure 11. Also shown in the figure is the amount of hydrogen that would be consumed to reduce the nitrogen content of a shale-oil syncrude. These large amounts of hydrogen would likely cause both economic and energy consumption penalties at the refinery.

The increasing trend toward higher-aromatic-content fuels, regardless of the crude source, will result in straight-distillation fuels with lower hydrogen content. The relation between hydrogen and aromatic contents is shown in Figure 12. At the currently specified aromatic content of 20 percent, the hydrogen content can vary between approximately 13.2 and 14.2 percent by weight. Within the band shown, the decrease in hydrogen content is generally a linear function with increasing aromatic content. An adverse effect of reduced hydrogen content is illustrated in Figure 13, where heat of combustion by weight is plotted as a function of hydrogen content. This effect is related to the effect of specific gravity shown in Figure 4 since reductions in hydrogen content result in proportionate increases in specific gravity. Substantial reductions in the heat of combustion occur with decreasing fuel hydrogen content. As an example, a reduction of approximately 1000 kilojoules per kilogram results when hydrogen content is reduced from 14 to 12 percent by weight.

In Figure 5 it is shown that Jet A fuel has a relatively narrow boiling range, with a final boiling point of approximately 270° C, which is necessary to comply with limits on the freezing point. The relation between freezing point and final boiling point is illustrated in Figure 14. The freezing point of a fuel is generally defined as the temperature at which wax components in the fuel begin to solidify. As shown in Figure 14, the freezing point is quite sensitive to variations in final boiling point.

The foregoing discussion considered only those fuel properties that are most likely to change. Potential increases in petroleum-crude aromatic content will result in decreased fuel hydrogen content unless additional hydrotreating is done at the refinery. Additional hydrotreating will surely be needed to reduce the nitrogen content and to increase the hydrogen content of fuels refined from oil shale and coal syncrudes if they are to meet current jet-fuel specifications. Hydrocracking will also be required to convert higher-boiling-range fractions to the boiling range and composition of current-specification jet fuels. These projected needs for additional hydrotreating will surely increase the cost of future-specification fuels and energy consumption required to refine them. Therefore, some relaxation of the current specifications may be needed to minimize

the adverse impact on cost and energy consumption. Several of the major fuel properties that could be affected by such a relaxation are shown in Table V. The values in the table are levels that have been suggested (11), as being reasonable for setting the possible limits of a candidate "broad-specification" fuel.

Measurement Techniques

As was pointed out in the preceding discussion, an accurate knowledge of the level of certain critical fuel properties is needed to evaluate the level of other dependent properties. The current methods for measuring several key fuel characteristics are shown in Table VI and are also compared with test methods that may be required for future fuels. It may be necessary to modify or replace current laboratory test methods for fuels with broadened specifications because test results using certain methods may be unacceptable when fuel property values exceed the range of sensitivity of current methods. Since hydrogen content is one of the key fuel properties, a direct measurement of hydrogen content should be made by using a technique such as nuclear magnetic resonance (NMR). Also, the hydrocarbon composition may be needed to determine its effect, if any, on combustion and thermal stability characteristics. Gas chromotography - mass spectrometry (GCMS) is a likely candidate for hydrocarbon analysis. New techniques to measure volatility, fluidity, and thermal stability will also be valuable to more accurately determine the volatility of high-boiling-range fuel, correlations between freeze point and pumpability, and correlations between fuel deposition and engine life. Finally, techniques such as the Kjeldahl method will be needed for measuring the nitrogen content of future syncrude-derived fuels.

FUEL PROPERTY EFFECTS

The preceding sections of this paper described and discussed fuel properties that are most likely to change in future broad-specification fuels. In this section, the effect of varying these properties on the combustion and thermal oxidation characteristics of future fuels is considered.

Flame Characteristics

The fuel property that has the largest effect on the characteristics of the flame within a gas-turbine combustor is the hydrogen content of the fuel. It affects soot formation, carbon deposition, flame temperature, and total flame radiation. The effect of hydrogen content on soot formation is shown in Figure 15 (taken from ref. 12), where the soot concentration is shown to increase markedly with decreasing hydrogen content. These results were obtained by collecting soot samples from the primary zone of an experimental atmospheric burner at near-stoichiometric conditions for blends of benzene and n-heptane. The tendency to form soot is a function not only of hydrogen content but also of combustor inlet pressure and temperature and primary-zone equivalence ratio. The results shown in Figure 15 were obtained in a very carefully controlled experiment and may not be typical of the actual characteristics that would occur in a gas-turbine combustor. Soot formation rate can also be affected by the atomization quality and vaporization rate of the fuel being injected into the flame zone. Both volatility and viscosity can affect these processes. The calculated effect of fuel viscosity on drop-size distribution of a typical fixed-orifice fuel nozzle is illustrated in Figure 16 (taken from ref. 13).

The effect of hydrogen content on carbon deposition characteristics is illustrated in Figure 17 (taken from ref. 14). Also included in this figure is the effect of volatility. Figure 17(a) shows the effect of hydrogen content (hydrogen-carbon weight ratio) and volatility (volumetric average boiling temperature) on a correlating parameter, the NACA K factor. The effect of NACA K factor on average carbon deposition in a single-can combustor operating for 4 hours at a pressure of about 2 atmospheres, an inlet temperature of 130° C, and a fuel-air ratio of 0.0123 is illustrated in Figure 17(b). Both increases in boiling temperature and decreases in hydrogen content resulted in increases in the NACA K factor (Fig. 17(a)) and, therefore, increases in the average carbon deposition (Fig. 17(b)). The fuel properties were varied by "doping" a MIL specification fuel to get the desired characteristics. The carbon deposition results shown in Figure 17(b) were obtained in a single-can combustor operating at relatively low inlet temperature and pressure and are not necessarily typical of advanced high-pressure-ratio, gas-turbine-engine combustors. Fuel injector characteristics can also affect these relations; hence fuel viscosity is also an important fuel property when evaluating carbon deposition characteristics.

Figure 18 shows the calculated effect of hydrogen content on maximum flame temperature within a combustor at simulated takeoff and cruise conditions (ref. 15). This increasing flame temperature characteristic with decreasing hydrogen content can have several adverse effects within an aircraft engine combustor. Both the rate of oxides-of-nitrogen (NO_x) formation and the total flame radiation energy would increase. A more dramatic impact of hydrogen content on flame radiation is shown in Figure 19 (taken from ref. 16), where total radiant energy is plotted as a function of combustion pressure and fuel hydrogen content. Two distinct characteristics are observable: (1) total radiant energy increases dramatically as the hydrogen content of the fuel is decreased at a con-

stant combustion pressure; and (2) total radiant energy increases significantly as combustion pressure is increased at a constant fuel hydrogen content. Reducing hydrogen content or increasing pressure both increase soot concentrations and thus increase flame luminosity.

Emission Characteristics

The effect of fuel properties on the formation of pollutants manifests itself in both soot (particulate) and gaseous emissions. The effect of hydrogen content on the smoke emissions of a single-can combustor is shown in Figure 20 (taken from ref. 15). Over the range of hydrogen content tested, a nearly twofold difference in smoke number was measured. The effect of hydrogen content on the NO_x emissions of this combustor is shown in Figure 21 (also taken from ref. 15). The increase in NO_x emissions noted is attributed to the increase in maximum flame temperature that was illustrated in Figure 18. The combined effect of hydrogen content and fuel volatility on the formation of total unburned hydrocarbon (HC) and carbon monoxide (CO) emissions in a single-can combustor is shown in Figure 22 (taken from ref. 17). The largest effect is at the low-power operating conditions, where low pressure, temperature, and fuel-air ratio are all conducive to poor combustion efficiency and, hence, high CO and HC emission levels. Reducing fuel volatility and hydrogen content (i.e., going from a Jet B (JP-4) to a no. 2 diesel fuel (DF-2)) resulted in a more than twofold increase in HC emissions and a 50-percent increase in CO emissions at the lowest power condition (idle). The increases in the CO and HC emissions are most likely the result of poor fuel atomization and vaporization characteristics.

One other fuel property that affects the formation of pollutant emissions is shown in Figure 23 (taken from ref. 18), where the NO_x emissions of a single-can combustor are plotted as a function of fuel-bound-nitrogen content for various simulated engine operating conditions. At all operating conditions, increasing fuel-bound nitrogen resulted in substantial increases in the NO_x emissions. These increases are caused by the conversion of fuel-bound nitrogen to nitric oxide. The conversion rate for this process can vary from about 50 percent to 100 percent, depending on combustion geometry and operating conditions.

Ignition Characteristics

Two fuel properties that have a significant effect on the ignition characteristics of a fuel are volatility and viscosity. Viscosity plays an important role in determining the effectiveness of a fuel injector in atomizing the fuel into small, easily ignitable droplets. (Fig. 16.) The ignition limits of several fuels are plotted as a function of combustor primary-zone equivalence ratio in Figure 24 (taken from ref. 17). Significantly higher primary-zone equivalence ratios (higher injector fuel flows) were needed to successfully ignite the higher-boiling-range fuels than to ignite the lower-boiling-range, more volatile JP-4 fuel. For the operating conditions chosen for these tests, no. 2 diesel fuel (DF-2) could not be ignited without adding a blending fuel (10-percent pentane). One other characteristic shown in this figure is also worth mentioning: For any given fuel, the time to start can be dramatically affected by the flow rate through the injector, as indicated by variations in primary-zone equivalence ratio. The injector spray pattern can be severely distorted at low fuel flow rates (low nozzle pressure drop) especially for the more viscous fuels.

Throughout the foregoing discussion, the effects of selected fuel properties on combustion and emission characteristics were described. It was pointed out that several fuel properties may combine to produce a particular adverse effect and that it is not always clear which property is the predominant factor. Nonetheless, certain trends can be attributed to particular fuel properties and, therefore, changes in these properties in future fuels will cause results similar to those that were illustrated. Therefore, if fuel properties change in accordance with the proposed broad-specification fuel described in the preceding section of this paper, we can expect to be faced with the need to evolve advanced technology to minimize the adverse impacts on combustion, emission, and ignition that have been discussed.

THERMAL STABILITY

Aircraft jet fuels must be stable at the temperatures that they will encounter in the fuel system. No gums or deposits should occur on heated surfaces such as heat-exchanger tubes and no cracking or particulate formation should occur that could clog small passages such as those in fuel nozzles. Laboratory tests that have been developed to check on this particular fuel behavior subject the fuel to a thermal stress in a test rig such as that shown schematically in Figure 25. A small tube is heated electrically to the test temperature. The fuel flows up through an annulus surrounding this heated surface and out through a test filter. During this procedure, any tendency of the fuel to form particulates large enough to block the test filter can be noted by a buildup of pressure drop across the filter. At the same time, deposits may also form on the heated tube. Any chemical changes bringing about the fuel instabilities should occur at an increased rate

as the fuel temperature is increased. In general, either the pressure drop across this test filter increases at a faster rate or the indicated deposits on the tube build up at a faster rate, as the test temperature is increased. Thus, one way of comparing the thermal stabilities of fuels is to determine the maximum temperature of the heated tube before the test exceeds certain specified limits of pressure drop or tube deposit buildup. This temperature is then referred to as the "breakpoint temperature."

Breakpoint temperatures for a number of oil-shale- and coal-derived fuels were determined by using the test apparatus shown in Figure 25 (taken from ref. 19). The results are shown in Figures 26 and 27, where the breakpoint temperatures were determined from tube deposit buildup, which turned out to be the limiting factor. Figure 26 shows the effect of fuel-bound-nitrogen content on breakpoint temperature for several oil-shale-derived fuels. The variation in fuel-bound-nitrogen content was controlled by hydrotreating the fuels to different degrees of severity. The effect of the fuel-bound-nitrogen content is significant, and these data indicate that nitrogen content in excess of 0.01 percent by weight would reduce the breakpoint temperature to levels below the minimum allowable for current Jet A fuel. Therefore, crude oils with high fuel-bound-nitrogen content would have to be hydrotreated to meet current fuel specifications. Although it is known that fuel-bound nitrogen is a factor contributing to the instability of fuels, it is not possible to determine if it is solely responsible for the stability difference shown in Figure 26.

Figure 27 shows the breakpoint temperature for some coal-derived fuels as a function of the weight percentage of hydrogen. The fuel-bound nitrogen in all the fuels was 6 ppm or less. In this case, a general trend was to higher breakpoint temperatures as the hydrogen content was increased: A 260° C breakpoint generally required at least 13-percent hydrogen content. Typical Jet A, which has a hydrogen content of about 13.5 to 14 percent, must have a breakpoint temperature greater than 260° C.

Another factor that affects breakpoint temperature is the final boiling point of jet fuels. Figure 28 shows the decreasing trend that breakpoint temperature follows for fuels from two different syncrudes as the final boiling point of the fuels is increased. The difference in level between the two curves is most likely caused by differences in hydrogen and fuel-bound-nitrogen content. Figures 26 to 28 present some of the early stability data available on turbine fuels from synthetic sources and indicate the general severity of the refining processing that would be required to produce synthetic fuels with stabilities comparable to those of current jet fuels.

CONCLUDING REMARKS

The available sources of petroleum crude oil that are used to produce aircraft engine jet fuel have been slowly undergoing changes in several critical properties. Foremost among these changes is the slow average increase in the content of aromatic compounds and several rather large increases in these compounds that have recently occurred or are projected to occur (e.g., in Alaskan crude oil). These large increases in aromatic content have led to considerable concern regarding the hydrogen content in jet fuels derived from these crude-oil sources. Making up for future shortages of middle-distillate fractions by "cracking" higher-boiling-range petroleum fractions would also result in higher-aromatic-content jet fuels unless hydroprocessing were used to upgrade these fuels to current-specifications. In addition, initial evaluations of the characteristics of jet fuels that could be refined from syncrudes obtained from oil shale and coal have shown that considerable hydrotreating will be needed to upgrade the hydrogen content of these fuels to satisfy current specifications. Along with these concerns about hydrogen content, indications are that variations in fuel-bound-nitrogen content, boiling range, freezing point, and trace constituents may all be encountered in future fuels, especially in those derived from syncrudes. In this paper, the effect of varying all the aforementioned fuel properties on the combustion and thermal stability characteristics of a fuel were described and discussed. A knowledge of how severe the effects of variations in hydrogen content, fuel-bound-nitrogen content, and boiling range are on such combustion phenomena as soot and carbon formation, emissions, and ignition, is going to be needed. The severity of these related effects will be an important consideration in determining the tradeoff between the cost and energy consumption needed at the refinery to produce current-specification fuel and the cost of developing new engine combustion chambers that can use broaden-specification fuel.

To provide a common basis for obtaining the data needed for this tradeoff, a specification for a reference-type fuel was developed at a workshop conducted at the NASA Lewis Research Center (11). The proposed specifications for this experimental referee broad specification (ERBS) aviation turbine fuel are presented in Table VII. Both the proposed specification levels and the measurement techniques for determining these levels are shown. The principal properties that have been "broadened" are those that have been discussed in this paper: composition (hydrogen content), volatility (boiling range), fluidity (freezing point and viscosity), and thermal stability (breakpoint temperature). The use of this common broad-specification fuel in experiments conducted by many investigators should provide a basis for maximizing the usefulness of basic studies as well as a basis for comparing the ability of future aircraft-engine combustors to successfully operate with a broad-specification fuel. Future experimental studies should not and will not be confined to the ERBS fuel. Continued effort is still needed to parametrically evaluate the impact that large variations in properties, as discussed in this paper, has on the combustion and thermal stability characteristics of future fuels.

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TABLE I. - COMPOSITION OF PETROLEUM CRUDE OILS

Crude source	Constituents	Total crude	Middle-distillate fractions		
			Boiling point, °C		
			120 - 205	205 - 275	275 - 345
		Content, wt%			
Nigeria (light)	Sulfur	0.14	0.02	0.09	0.17
	Nitrogen	.12	.001	.001	.012
	Hydrogen	13.0	13.4	13.1	12.8
Aga-Jari, Iran	Sulfur	1.34	0.04	0.40	0.95
	Nitrogen	.13	.001	.004	.010
	Hydrogen	13.0	14.3	13.6	13.1
Kuwait	Sulfur	2.53	0.10	0.45	1.52
	Nitrogen	.13	.001	.092	.10
	Hydrogen	12.7	14.2	13.8	13.1
Alaska (Prudhoe Bay)	Sulfur	1.04	0.05	0.23	0.60
	Nitrogen	.23	.001	.009	.028
	Hydrogen	12.3	13.8	13.0	12.7

TABLE II. - COMPOSITION OF "SYNTHETIC" CRUDE OILS

Crude source (process)	Con-stituents	Total crude	Middle-distillate fractions		
			Boiling point, ^{o}C		
			120 - 205	205 - 275	275 - 345
		Content, wt%			
Shale oil (Paraho)	Sulfur	0.71	0.90	0.66	0.69
	Nitrogen	2.0	.001	1.01	1.9
	Hydrogen	11.5	12.5	12.2	11.5
Shale oil (Tosco)	Sulfur	0.67	0.85	0.82	0.75
	Nitrogen	1.85	1.0	1.45	1.86
	Hydrogen	11.6	13.1	12.3	11.5
Shale oil (Garrett-Insitu)	Sulfur	0.64	0.65	0.56	0.60
	Nitrogen	1.30	.001	.46	1.03
	Hydrogen	11.8	12.6	12.5	12.0
Coal syncrude[a] (Synthoil)	Sulfur	0.22	0.10	0.092	0.14
	Nitrogen	.79	.30	.29	.32
	Hydrogen	9.2	11.0	10.8	10.4

[a]Kentucky coal.

TABLE III. - CHARACTERISTICS OF AVIATION TURBINE FUEL

Characteristic	Effect or relevance
Heat of combustion	Specific fuel consumption; takeoff gross weight
Specific gravity	Heat of combustion (by weight, by volume)
Volatility	Ignition; altitude relight; idle emissions; evaporation loss; carbon formation
Viscosity	Fuel atomization; ignition; pumpability
Aromatics (H/C)	Smoke; flame radiation; heat of combustion; carbon formation; thermal stability
Flashpoint	Fire safety
Freezing point	Pumpability on high-altitude, long-range missions
Sulfur	Corrosion; emissions
Olefins	Gum formation (thermal stability)
Thermal stability	Maximum fuel temperature; fuel deposition

TABLE IV. - SPECIFICATIONS FOR AVIATION TURBINE FUEL

	ASTM D1655-77 standard specification for aviation turbine fuel		Average properties of Jet A (1976 ERDA)
	Jet B	Jet A, Jet A-1[b]	
Composition: maximum content of -			
Aromatics, vol%	20	20	17.0
Sulfur (total), wt%	0.3	0.3	0.06
Naphthalenes, wt%	-------------	[a]3	1.70
Olefins, vol%	-------------	[a]5	1.10
Volatility:			
Distillation temperature (max.), °C:			
Initial boiling point	-------------	-------------	171
10% recovered	-------------	204	188
20% recovered	143	-------------	195
50% recovered	188	[a]232	213
90% recovered	243	Report	246
Final boiling point	-------------	300	267
Flashpoint (min.), °C	-------------	37.8	53.7
Reid vapor pressure (max.), kPa	20.7	-------------	
Specific gravity (15° C/15° C)	0.751 - 0.802	0.775 - 0.840	
Fluidity:			
Freezing point (max.), °C	-50	[b]-40	-46
Viscosity at -34° C (max.), m^2/s (cS)	-------------	[c]15×10^{-6}	9.3×10^{-6}
Net heat of combustion (min.), kJ/kg	42 800	42 800	43 280
Thermal stability (JFTOT breakpoint temperature, °C)	260	260	--------

[a]Value is from earlier specifications; current specifications omit this.
[b]Jet A-1 freezing point is -50° C.
[c]Current viscosity specification is 8×10^{-6} m^2/s (cS) at -4° C.

TABLE V. - MAJOR PROJECTED CHANGES IN FUEL PROPERTIES

	Current Jet A	Future broad-spec fuel
Aromatic content, vol%	17 - 25	30 - 35
Hydrogen content, wt%	14 - 13.5	13.0 - 12.5
Final boiling point, $^{\circ}C$	260 - 280	290 - 330
Freezing point, $^{\circ}C$	-46 - -40	-34 - -29
Thermal stability (JFTOT breakpoint temp, $^{\circ}C$)	≥ 260	≥ 240

TABLE VI. - CURRENT AND FUTURE FUEL-CHARACTERIZATION METHODS

Fuel characteristic	ASTM method (current specification)	Test method for future fuel (broad specification)
Composition:		
Aromatic content, vol%	Fluorescent indicator absorption (ASTM D1319-77)	Direct determination of hydrogen weight percent, i.e., by nuclear magnetic resonance, for higher aromatics
Naphthalene content, vol%	Ultraviolet spectrography (ASTM D1840-64)	Hydrocarbon compositional analysis, i.e., gas chromatography - mass spectroscopy, for synfuels
Nitrogen, ppm	None	Kjeldahl or equivalent approach, for nitrogen-containing fluids
Volatility	ASTM distillation (D86-77) or other methods	Simulated distillation by gas chromatography, for high-boiling-point fuels
Fluidity	Freezing point determination (ASTM D2386-67)	Pumpability test for high-freezing-point fuels or correlation of freezing point with pumpability
Thermal stability	CRC coker (ASTM D1660-72) or jet-fuel thermal oxidation test (ASTM D3241-77)	Improved correlation with engine deposition and life; improved test methods

TABLE VII. - PROPOSED SPECIFICATIONS FOR EXPERIMENTAL REFEREE BROAD-SPECIFICATION (ERBS) AVIATION TURBINE FUEL

Specification	ERBS jet fuel	Proposed test method
Composition:		
Hydrogen content, wt%	12.8±0.2	Nuclear magnetic resonance
Aromatic content, vol%	Report	ASTM D1319
Sulfur content (mercaptan), wt%	0.003 (max.)	ASTM D1219
Sulfur content (total), wt%	0.3 (max.)	ASTM D1266
Nitrogen content (total), wt%	Report	Kjeldahl
Naphthalene content, vol%	Report	ASTM D1840
Hydrogen compositional analysis	Report	Gas chromatography - mass spectroscopy
Volatility:		
Distillation temperature, °C		
Initial boiling point	Report	ASTM D2892
10% recovered	205 (max.)	↓
50% recovered	Report	↓
90% recovered	260 (min.)	↓
Final boiling point	Report	↓
Residue, percent	Report	↓
Loss, percent	Report	↓
Flashpoint, °C	38 to 49	ASTM D56
Gravity, deg API at 15° C	Report	ASTM D287
Gravity (specific), (15° C/15° C)	Report	ASTM D1298
Fluidity:		
Freezing point, °C	-29 (max.)	ASTM D2386
Viscosity at -23° C, m^2/s (cS)	12×10^{-6} (max.)	ASTM D445
Net heat of combustion, kJ/kg	Report	ASTM D2382
Thermal stability (JFTOT breakpoint temperature, based on TDR = 13 or ΔP = 25 mm, °C)	240 (min.)	ASTM D3241

ACTION	ADVANTAGES	DISADVANTAGES
PRODUCE SPECIFICATION JET FUEL	OPTIMIZED FUEL PROPERTIES AIRCRAFT/ENGINE RETROFIT NOT REQUIRED	INCREASED REFINERY ENERGY CONSUMPTION INCREASED FUEL COST
RELAX JET FUEL SPECIFICATION	CONSERVATION OF ENERGY REDUCED FUEL COST	MORE COMPLEX COMPONENT TECHNOLOGY REQUIRED ADVERSE EFFECT ON ENGINE LIFE

Fig.1 Assessment of potential actions

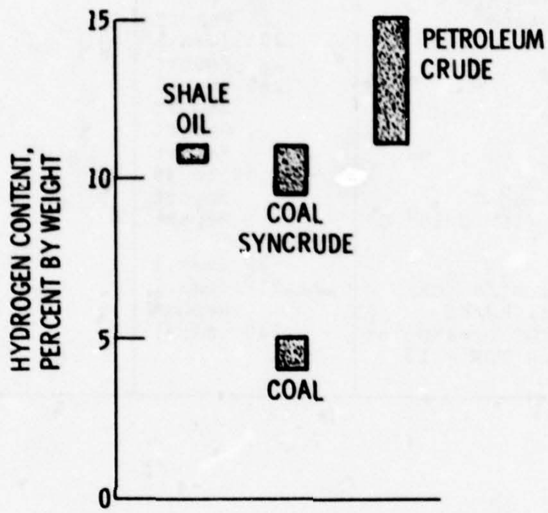

Fig.2 Hydrogen content of alternative sources of jet fuel

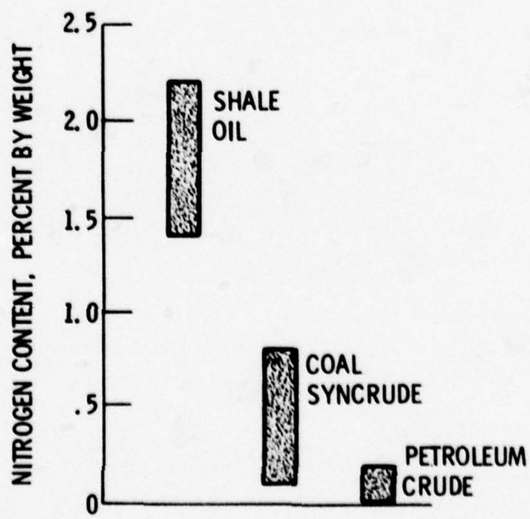

Fig.3 Nitrogen content of alternative sources of jet fuel

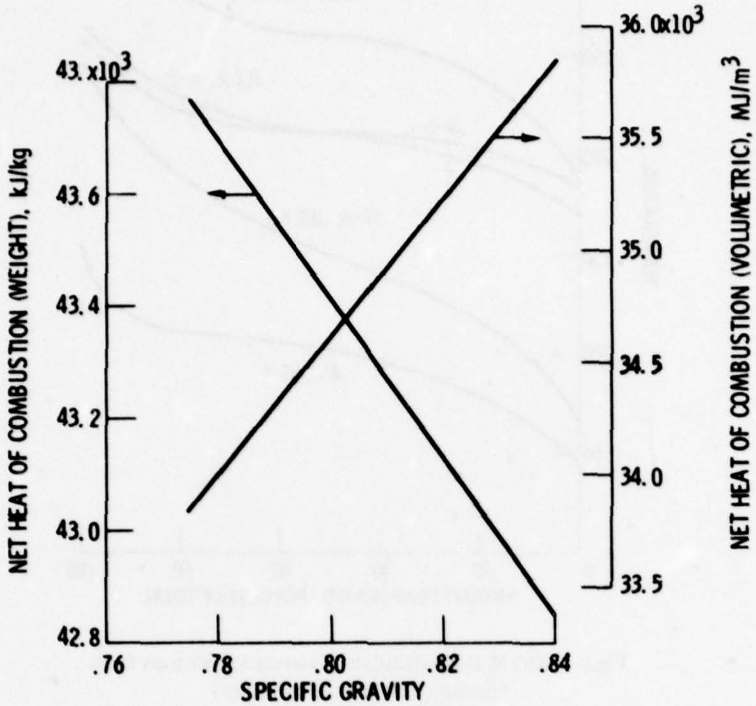

Fig.4 Effect of specific gravity of jet fuels on heat combustion by weight and volume

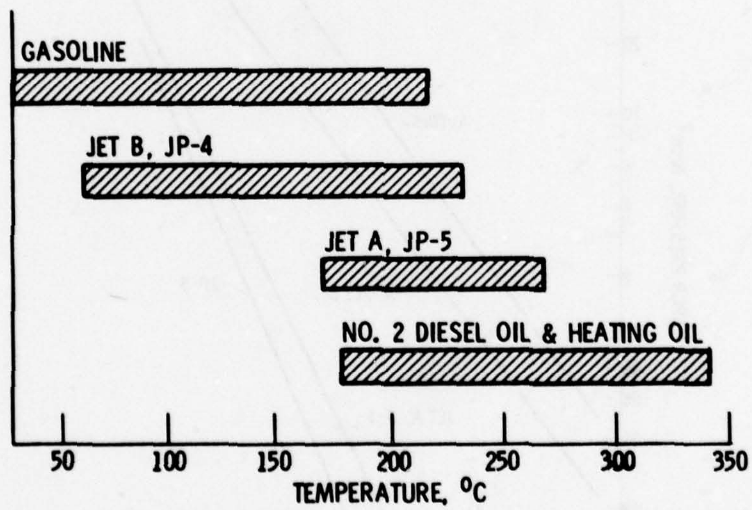

Fig.5 Boiling range of various petroleum products

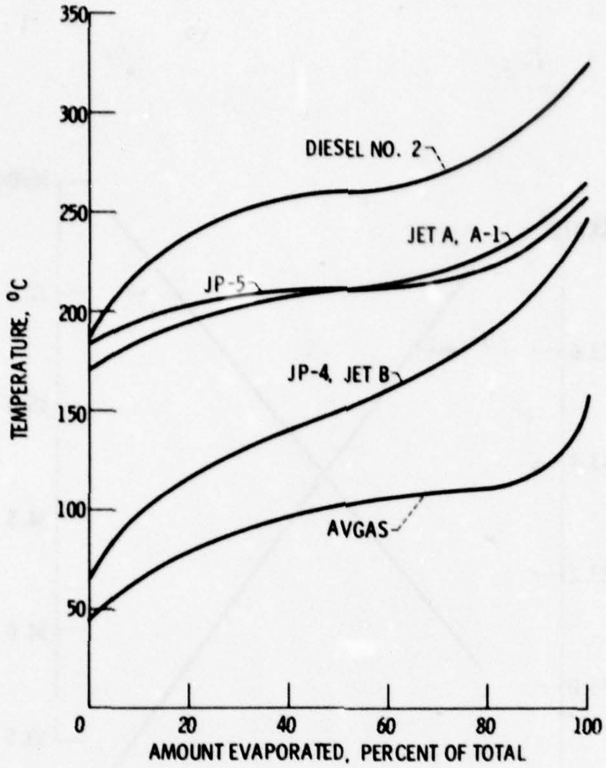

Fig.6 ASTM D-86 distillation curves for various fuels (Source, US Bureau of Mines)

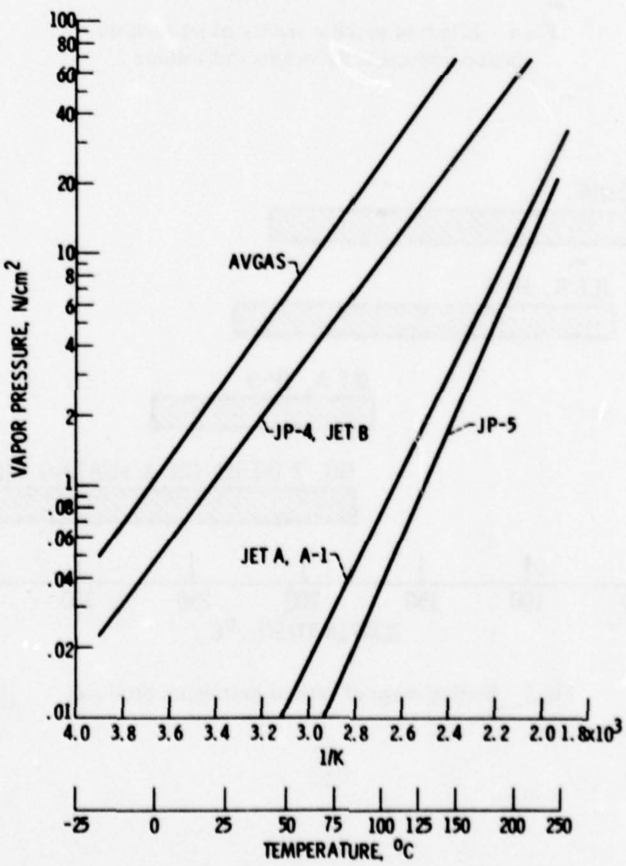

Fig.7 Effect of temperature on true vapor pressure of aviation fuels. (From Reference 20)

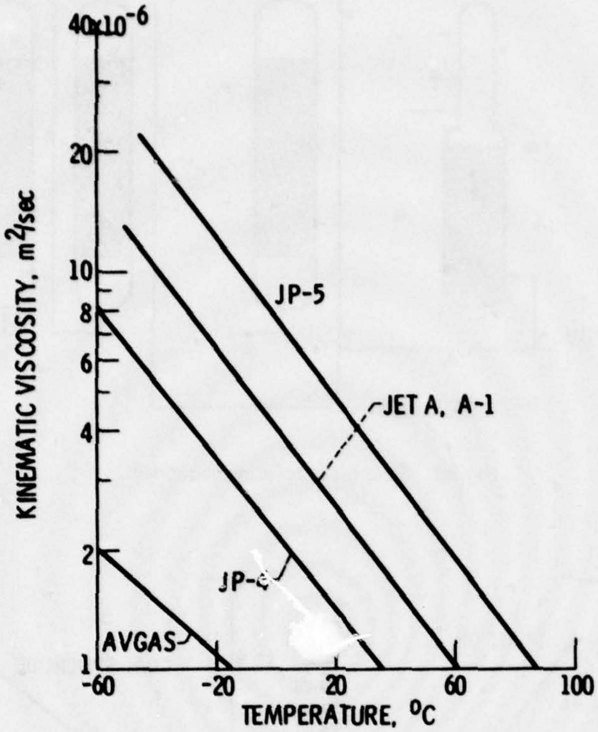

Fig.8 Effect of temperature on fuel viscosity. (From Reference 20)

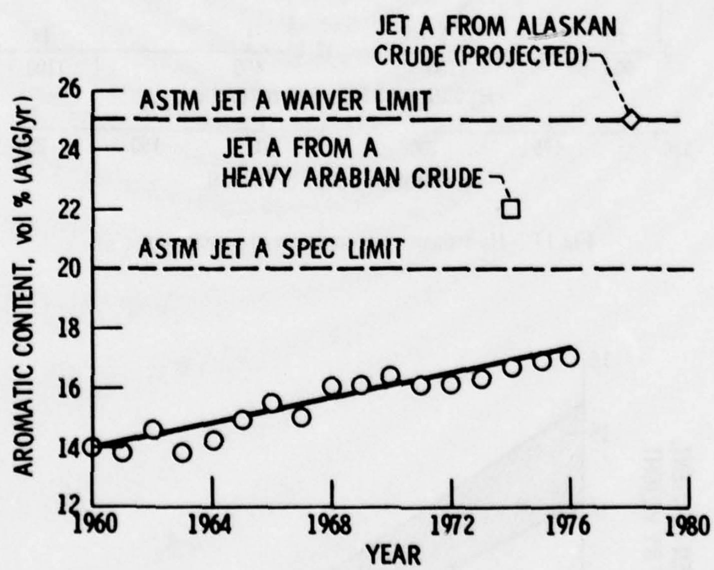

Fig.9 Trend in aromatic content of commercial Jet A fuel

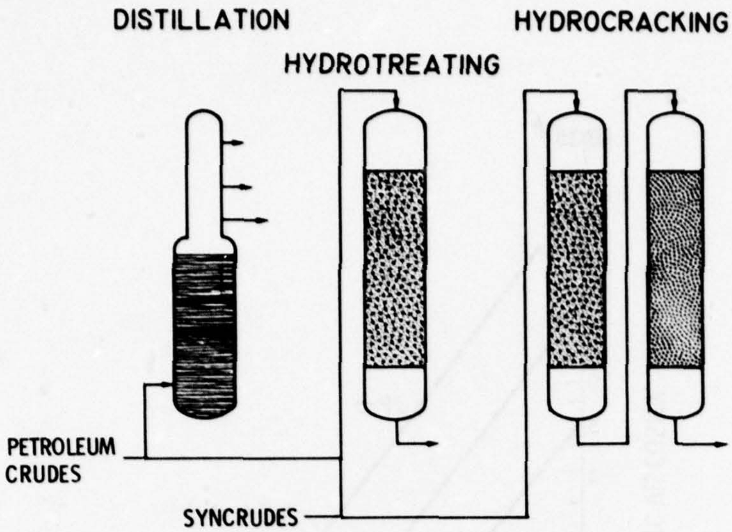

Fig.10 Simplified refining sequence

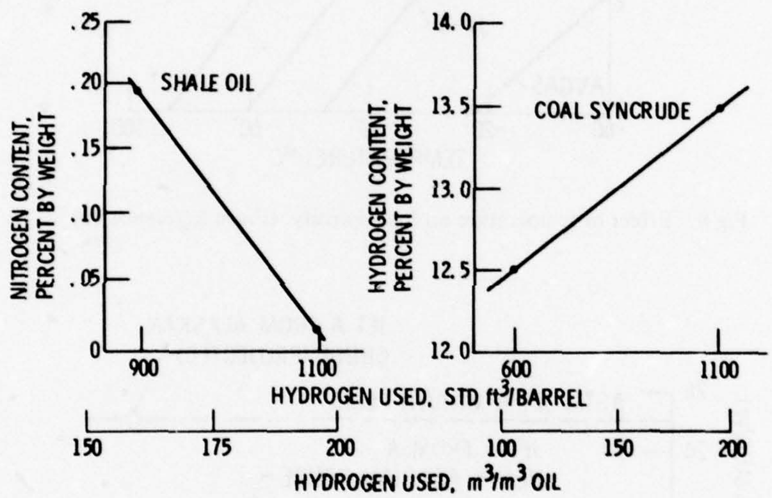

Fig.11 Hydrogen consumption in processing

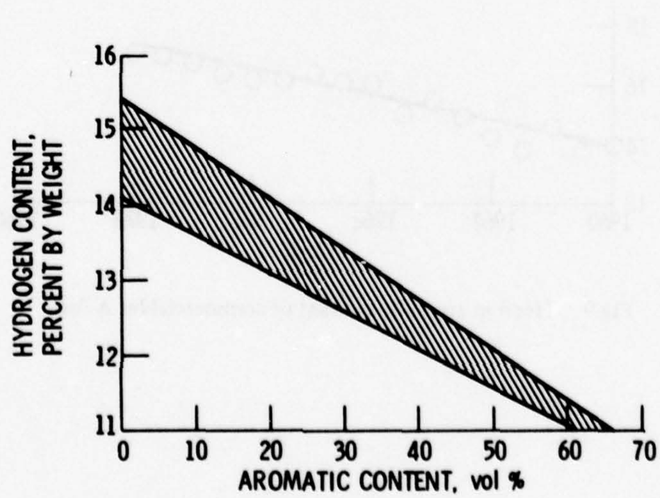

Fig.12 Relation between aromatic content and hydrogen content

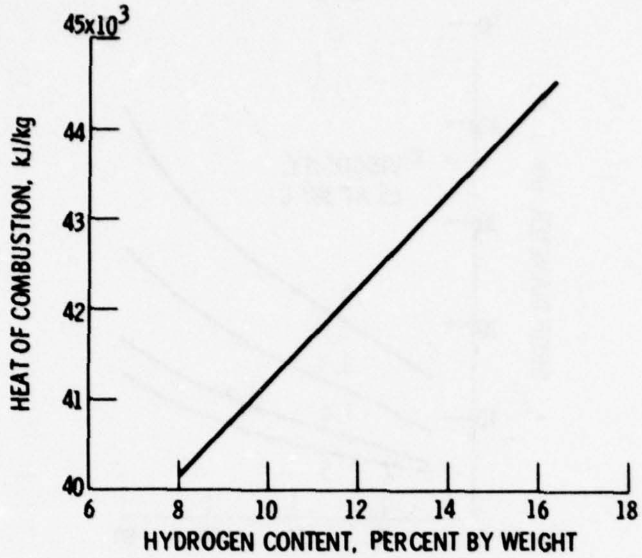

Fig.13 Effect of fuel hydrogen content on heat of combustion

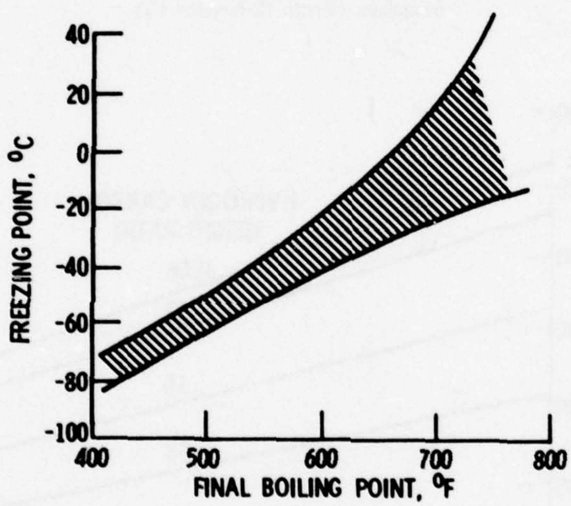

Fig14 Typical fuel-blend freezing points

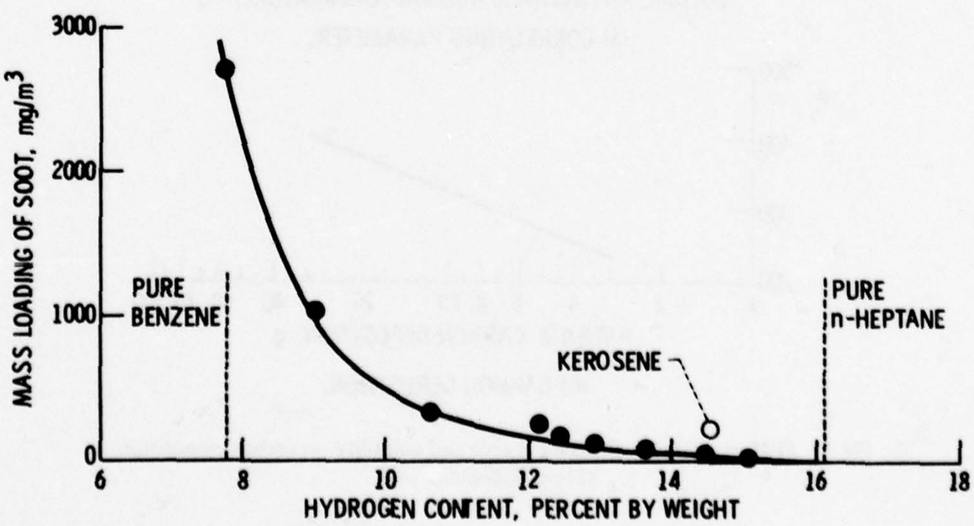

Fig15 Effect of fuel hydrogen content on peak soot concentration. (From Reference 12)

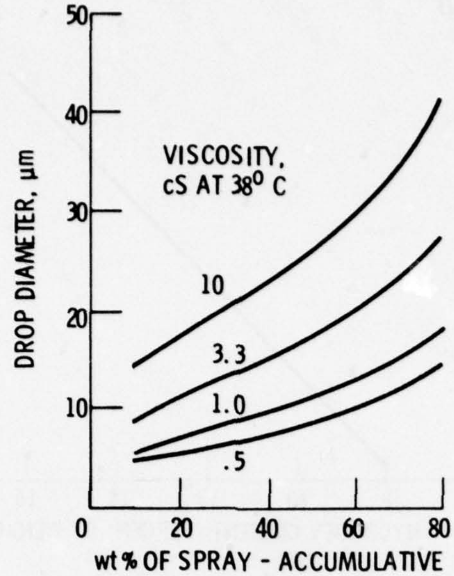

Fig.16 Calculated effect of fuel viscosity on drop size distribution of sprays. (From Reference 13)

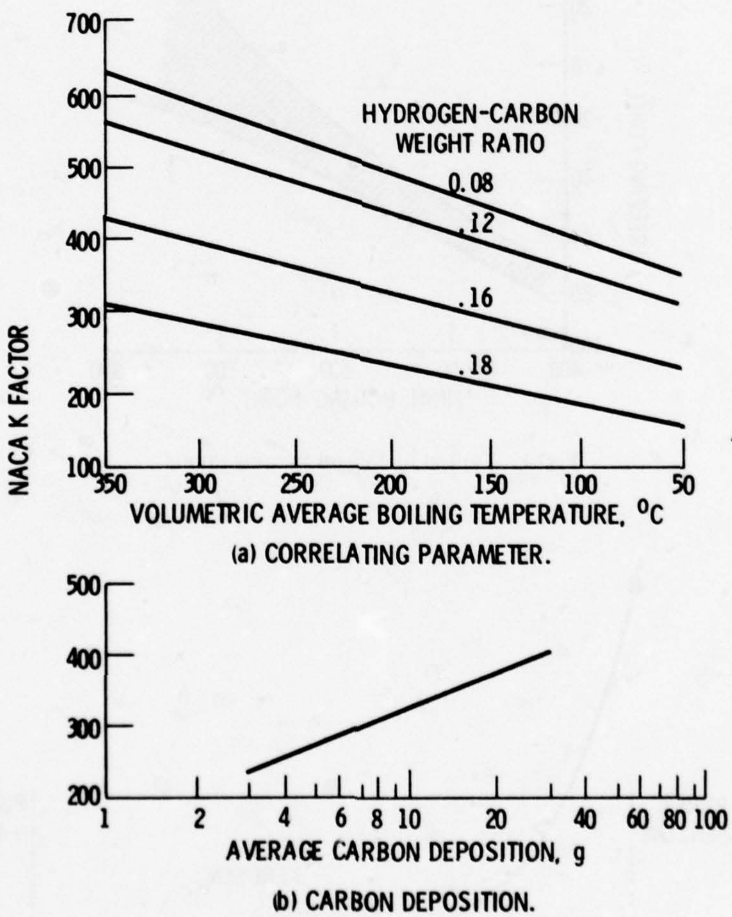

Fig.17 Effect of fuel hydrogen content and volatility on carbon deposition. (From Reference 14)

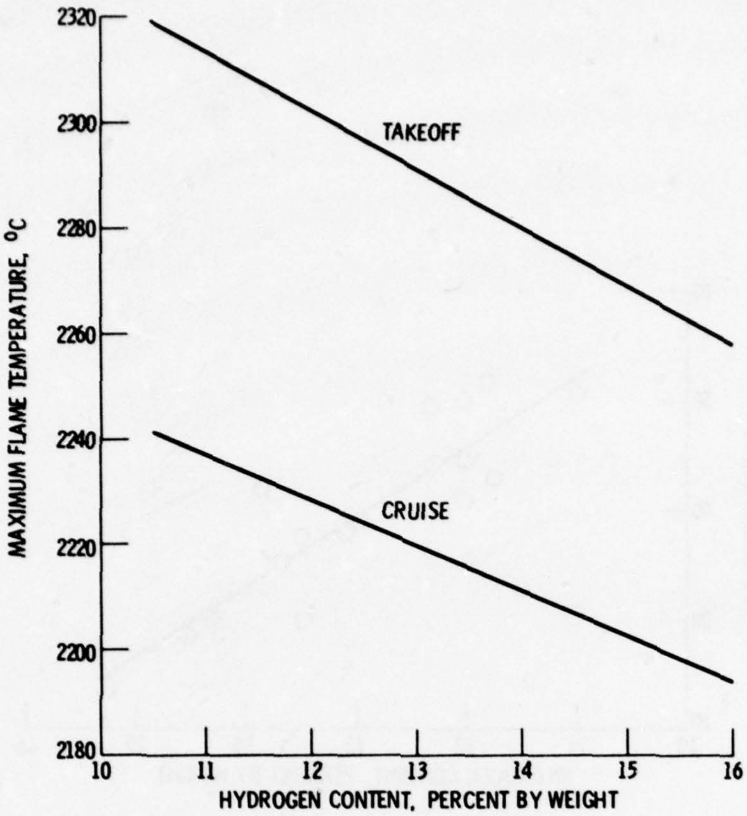

Fig.18 Effect of fuel hydrogen content on maximum flame temperature

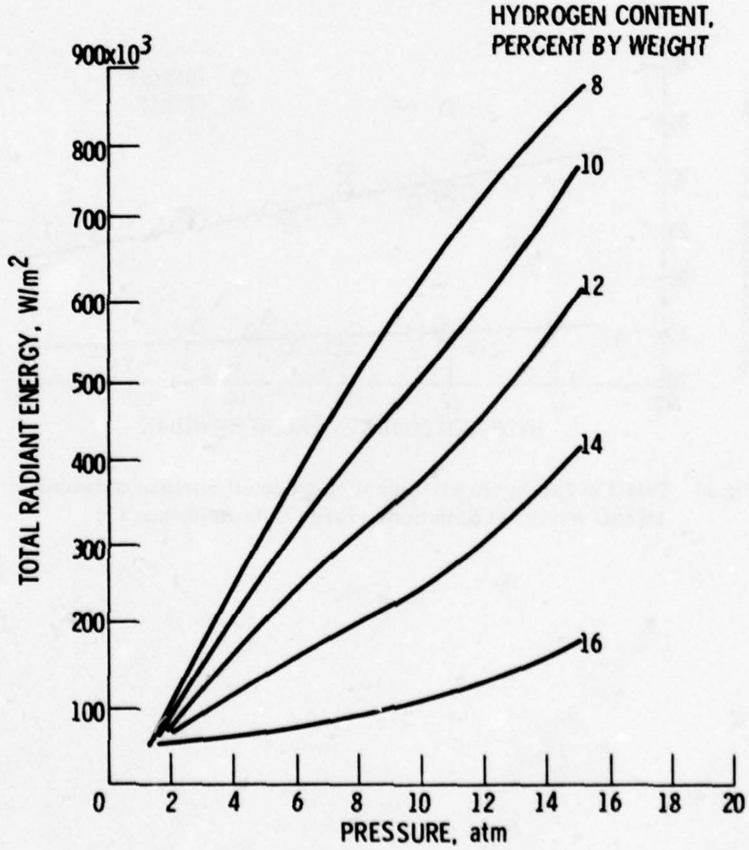

Fig.19 Effect of fuel hydrogen content and pressure on flame radiation. Inlet-air temperature, 430°C. (From Reference 16)

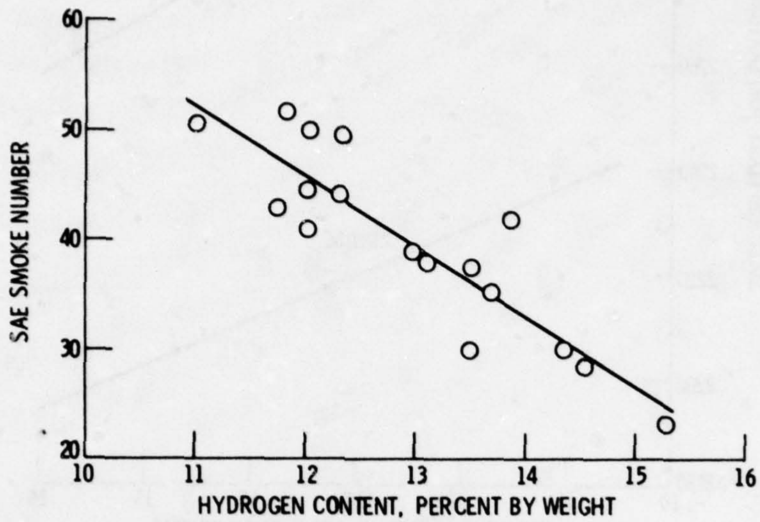

Fig.20 Effect of fuel hydrogen content on smoke number at takeoff condition. (From Reference 15)

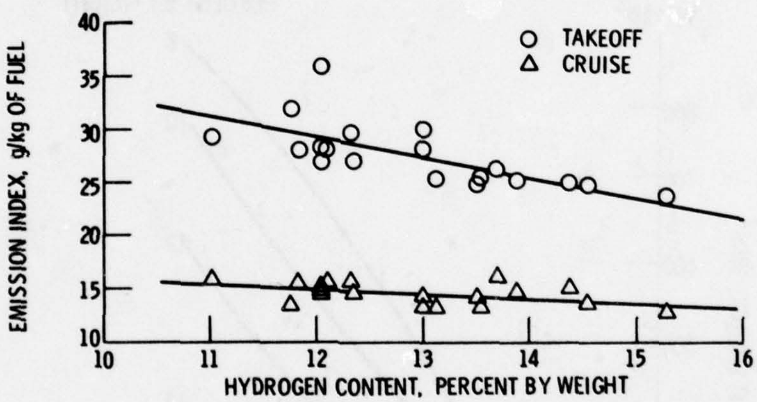

Fig.21 Effect of fuel hydrogen content on oxides-of-nitrogen emissions at takeoff and cruise conditions. (Taken from Reference 15)

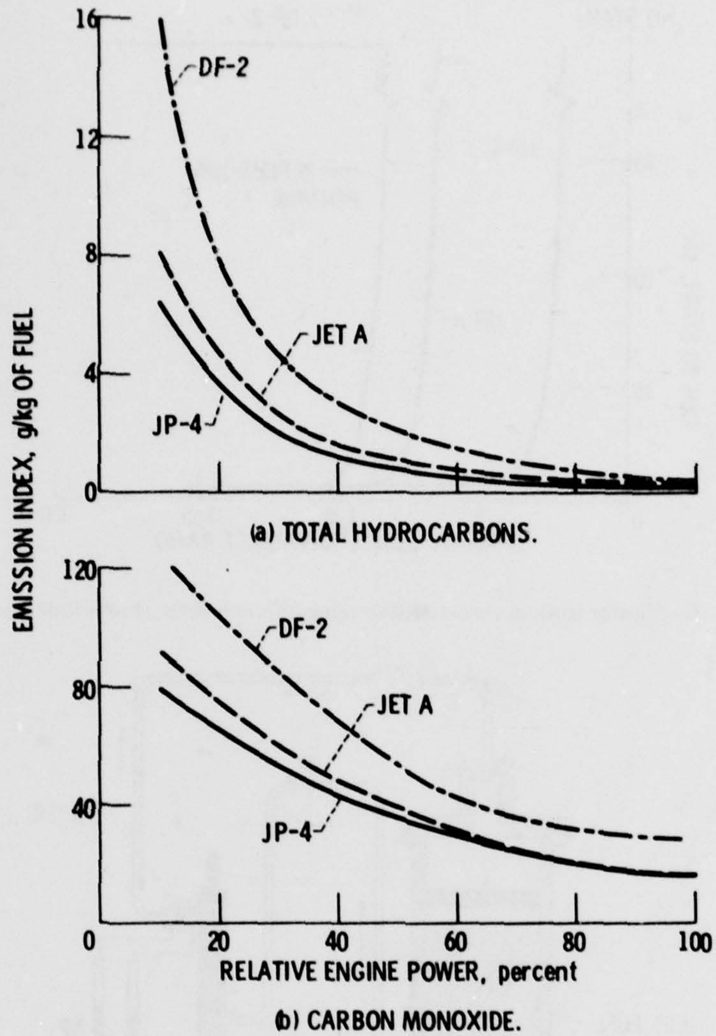

Fig.22 Effect of fuel type on total hydrocarbon and carbon monoxide emissions. (From Reference 17)

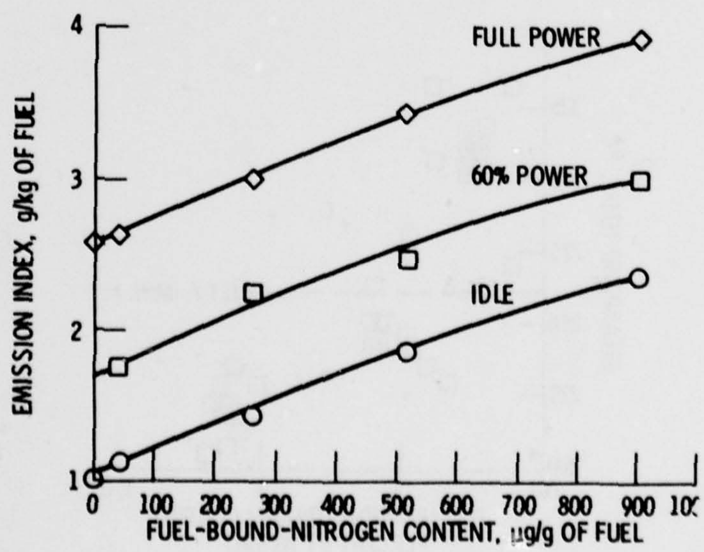

Fig.23 Effect of fuel-bound-nitrogen content on total emissions of nitrogen oxides. (From Reference 18)

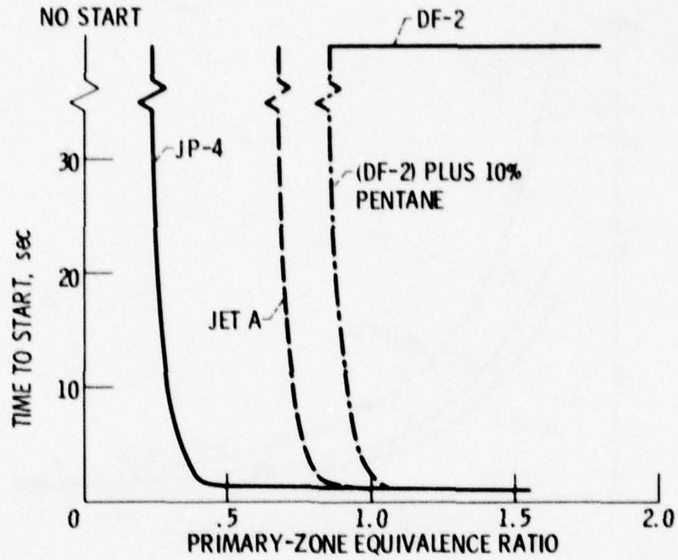

Fig.24 Combustor ignition characteristics using different fuels. (From Reference 17)

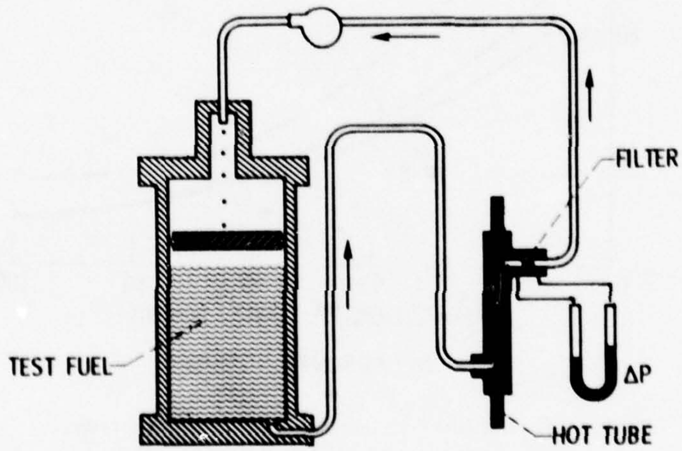

Fig. 25 Schematic of thermal-stability test rig. (From Reference 19)

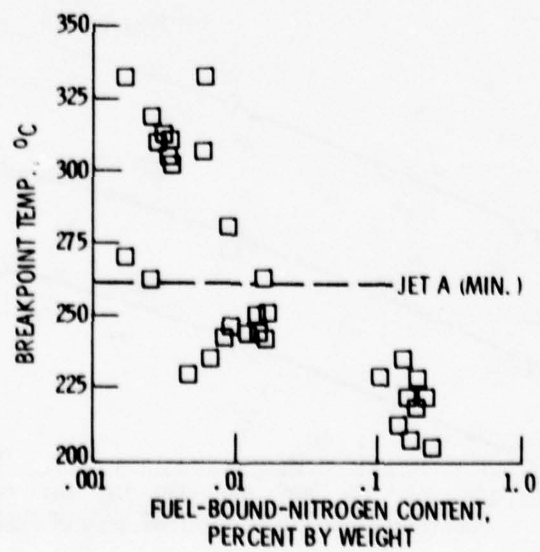

Fig.26 Effect of nitrogen level in oil-shale-derived fuels on breakpoint temperature

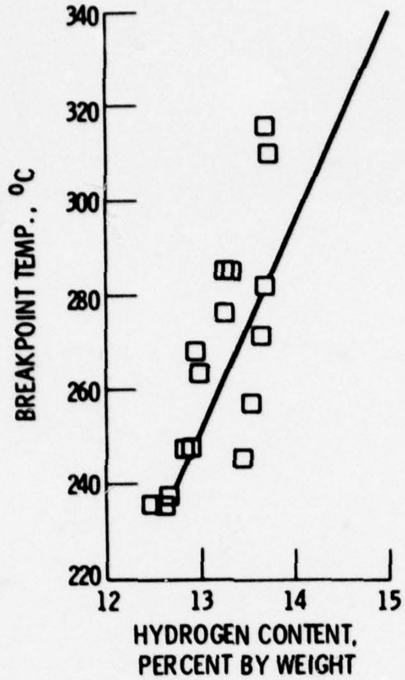

Fig.27 Effect of hydrogen content in coal-derived fuels on breakpoint temperature

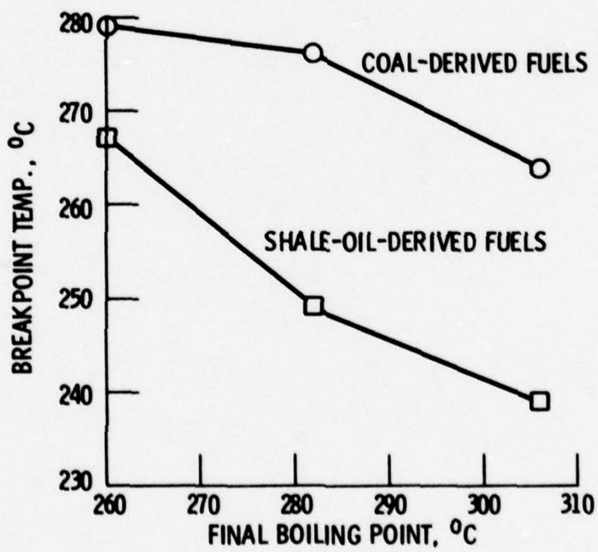

Fig.28 Effect of final boiling point on fuel thermal stability

IMPACT OF FUTURE FUEL PROPERTIES ON AIRCRAFT ENGINES AND FUEL SYSTEMS

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SUMMARY

From current projections of the availability of high-quality petroleum crude oils, it is becoming increasingly apparent that the specifications for hydrocarbon jet fuels may have to be modified. The problems that are most likely to be encountered as a result of these modifications relate to engine performance, component durability and maintenance, and aircraft fuel-system performance. The effect on engine performance will be associated with changes in specific fuel consumption, ignition at relight limits, at exhaust emissions. Durability and maintenance will be affected by increases in combustor liner temperatures, carbon deposition, gum formation in fuel nozzles, and erosion and corrosion of turbine blades and vanes. Aircraft fuel-system performance will be affected by increased deposits in fuel-system heat exchangers and changes in the pumpability and flowability of the fuel. The severity of the potential problems is described in terms of the fuel characteristics most likely to change in the future. Recent data that evaluate the ability of current-technology aircraft to accept fuel specification changes are presented, and selected technological advances that can reduce the severity of the problems are described and discussed.

INTRODUCTION

This paper describes and discusses the propulsion-system problems that will most likely be encountered if the specifications of hydrocarbon-based jet fuels must undergo significant changes in the future and, correspondingly, the advances in technology that will be required to minimize the adverse impact of these problems.

Future jet aircraft fuels derived from petroleum or "synthetic" crude stocks such as oil shale or coal may have significantly different fuel properties than current jet fuels. The effect of these changes in fuel properties on selected combustion processes are described and discussed in reference 1. As pointed out in reference 1, significant changes in fuel properties may be encountered in the not-too-distant future; the most probable changes will be in the hydrogen-to-carbon ratio, the percentage of aromatic compounds, the percentage of nitrogen compounds, and the fuel boiling range. The relationship of these fuel property changes to potential propulsion-system problems is illustrated in Figure 1. A higher fuel boiling range will likely result in a less volatile, more viscous fuel, which will affect both ignition characteristics and idle emissions, and a higher freezing point, which will affect the pumpability and flowability of the fuel. Increases in aromatic compounds will result in increased smoke and flame radiation and poorer chemical stability. Increases in nitrogen compounds will result in increased nitric oxide emissions and, again, poorer chemical stability. These potential problems impose some very severe constraints on the ability of conventional aircraft-engine technology to accommodate fuels with variations in these properties. Several investigations have been recently made or are currently under way to evaluate the effects of some of these property changes on conventional aircraft-engine technology (2-7). The principal problem areas that have been identified to date are primarily associated with the engine combustor and turbine and with both the engine and the aircraft fuel system.

Although this paper describes potential problems and the ability of advanced technology to minimize or eliminate them, in the final analysis, the choice between establishing allowable variations in fuel properties and implementing advanced propulsion-system technology will be arrived at through an iterative process. Obviously, economics will play a key role, as will the availability of high-quality crude oil feedstocks. Therefore, the criteria by which to make an optimum trade-off between future fuel specifications and advanced technological needs must be established. This is the principal objective of the Fuels Technology Program that is being conducted by the National Aeronautics and Space Administration (NASA) and from which a large part of the information presented in this paper was derived. Many other programs sponsored by both the U.S. Government and private industry are also under way, and they too have contributed information to this paper.

Several investigations conducted are summarized. Illustrations are used to describe the relative effects of selected fuel properties on the behavior of propulsion-system components and fuel systems. The selected fuel properties are those that are most likely to be relaxed in future fuel specifications (1). Illustrations are also used to describe technological advances that may be needed in the future. Finally, the technological areas needing the most attention are described, and programs that are under way to address these needs are briefly discussed.

STAR Category 07

ENGINE PERFORMANCE

Potential future fuel properties will generally affect engine performance by changing specific fuel consumption, ignition and relight limits, and exhaust emissions. Each of these factors is dealt with separately.

Specific Fuel Consumption

In general, the specific fuel consumption (SFC) characteristics of aircraft engines go through a cyclic deterioration with time (Fig. 2): A short-term engine performance deterioration, or increase in SFC occurs during early operation within the fleet; long-term engine performance deterioration is modified in a cyclic manner by engine repair. The short-term deterioration ordinarily results from changes in running clearances and tolerances in what might be called the break-in period; it is not generally recoverable. The long-term trend can be modified by engine repair; for the newer high-pressure-ratio engines this generally means replacement or refurbishment of hot-section parts. Many hot-section problems are caused by temperature maldistribution and by erosion and corrosion. Without the repair of hot-section parts, the overall long-term engine performance deterioration would be much greater than that shown on Figure 2. Relaxed fuel specifications, especially in the percentage of aromatic compounds and trace species such as vanadium and sulphur, may considerably aggravate long-term deterioration. The problems that may be caused by changes in aromatic content and trace species are described in more detail in the section ENGINE COMPONENT DURABILITY AND MAINTENANCE.

Ignition and Relight Limits

The principal fuel properties that affect the ignition and relight limits of an aircraft engine are volatility and viscosity. Fuel volatility and viscosity affect the atomization and vaporization characteristics of the fuel as it is sprayed into the combustion chamber. How these properties affect combustor ignition characteristics is illustrated in Figure 3 (taken from ref. 5), where time to start is plotted as a function of combustor primary-zone equivalence ratio for a JP4 fuel and a Jet A fuel. Two effects are clearly shown in Figure 3: For a given fuel (e.g., JP-4), the time to start increases dramatically with decreasing equivalence ratio after a critical minimum is reached. This is primarily due to the effect that reducing fuel-nozzle flow rate has on the atomization quality of the fuel spray. The second effect relates to fuel volatility and viscosity. Substituting a Jet A fuel for a JP-4 fuel, and thus varying volatility, made a higher primary-zone equivalence ratio necessary for successful ignition. The need to provide a richer primary-zone equivalence ratio could make it difficult to obtain adequate ignition limits for a fixed-geometry conventional combustor. Volatility and viscosity can also affect an engine's altitude relight envelope, as illustrated in Figure 4, for a modern high-bypass-ratio jet engine combustor using cold and heated JP-5 fuel. Reducing fuel volatility and increasing viscosity, as simulated by using the cold fuel, caused a noticeable loss in altitude relight capability, especially at the higher flight Mach numbers. Several techniques that can be used to improve relight are described later in this paper.

Exhaust Emissions

The principal fuel properties that can affect engine exhaust emissions are volatility, hydrogen content, and fuel-bound-nitrogen content. These properties affect all four of the principal exhaust emissions that have been designated as air pollutants and that are currently being regulated by the U.S. Environmental Protection Agency (EPA); carbon monoxide, hydrocarbons, nitrogen oxides, and smoke.

Effects of hydrogen content. - Fuel hydrogen content can affect all four pollutant emissions. Very dramatic increases in combustor smoke number with decreasing fuel hydrogen content have been obtained in experimental evaluations using conventional combustion chambers from current-technology aircraft engines. An example of this effect, for a conventional can-type combustor, is illustrated in Figure 5 (taken from ref. 6). At a simulated takeoff operating condition (Fig. 5(a)) the measured Society of Automotive Engineers (SAE) smoke number increased in a nearly linear manner as the percentage by weight of fuel hydrogen was reduced. The relative impact, as indicated by the slope of the experimental data, was more severe at the cruise and idle operating conditions, as shown in Figures 5(b) and (c), respectively. For the engine that uses this combustor, an SAE smoke number of 25 is required at takeoff for compliance with the currently proposed U.S. EPA standards.

The carbon monoxide (CO) and unburned hydrocarbon (HC) emissions of this same can combustor operating at idle conditions are plotted as a function of fuel hydrogen content in Figure 6 (taken from ref. 6). Although a considerable amount of scatter is evident, a trend of slightly increasing CO and HC emissions is detectable with decreasing fuel hydrogen content. This effect of fuel hydrogen content on CO and HC emissions will be most prevalent at the idle condition, as illustrated in Figure 7 (taken from ref. 5), where the emission characteristics of a low-pressure-ratio engine combustor are plotted as a function of the percentage of engine rated power for a variety of fuel types. Because the number 2 diesel fuel (DF-2) has a significantly lower hydrogen content and lower volatility than

the jet fuels, it produces higher emissions. The larger relative effect on emissions at idle, as compared with the other operating conditions, is attributed to the much lower compressor discharge pressure and temperature at idle. The effect of fuel hydrogen content on CO and HC emissions, as illustrated in this example, may not be as significant in current and future modern high-pressure-ratio engines. The higher compressor discharge pressures and temperatures of these engines should minimize this problem.

The effect of fuel hydrogen content on oxides of nitrogen (NO_x) emissions is illustrated in Figure 8 for the same can combustor used to obtain the results shown in Figures 5 and 6. For this combustor, the NO_x emission index increase was more pronounced at the takeoff condition than at the cruise condition. This increase in NO_x emissions was attributed to a possible increase in combustion flame temperature that could have occurred as the fuel hydrogen content was decreased. An example of such an increase in flame temperature is illustrated in Figure 9, where a computed maximum flame temperature (based on a homogeneous fuel-air mixture) is plotted as a function of fuel hydrogen content for the same cruise and takeoff test conditions used to obtain the experimental results shown in Figure 8. These theoretical temperature characteristics indicate that a trend toward increasing NO_x emissions with decreasing fuel hydrogen content should be expected.

Of all of these effects of fuel hydrogen content on exhaust emissions, the dramatic increases in smoke emission are felt to be the most severe and challenging problem.

Effects of fuel-bound-nitrogen content. - Increasing fuel-bound-nitrogen content is expected to have an effect only on NO_x emissions. This effect for a low-pressure-ratio engine combustor is illustrated in Figure 10 (taken from ref. 7) for three simulated engine operating conditions. The NO_x emissions increased substantially at all operating conditions as fuel-bound-nitrogen content was increased. The magnitude of the increase in NO_x emissions would be even more pronounced if all the nitrogen were converted into NO_x, but this was not the case, as shown in Figure 11. The conversion efficiency shown in Figure 11 is quite typical and comparable with many results currently being obtained in other experiments. In some studies, however, conversion efficiency has been shown to be a function of variations in combustor configuration and operating conditions. Conversion efficiencies from as high as 80 percent down to 40 or 50 percent have been realized.

In these experiments, fuel hydrogen and fuel-bound-nitrogen contents were varied by "doping" existing-specification fuels with such pure compounds as alkyl benzenes and pyridine. The range of hydrogen and nitrogen contents was purposely made large in order to evaluate the effects in a parametric manner. The lower and upper limits were not set to imply that any particular levels are expected in future fuels. Also, bear in mind that most of the results were obtained in controlled combustor test-rig experiments and thus may not be comparable to actual engine results. Nevertheless, the trends in exhaust emissions that were illustrated are felt to represent what can be expected if fuels having properties similar to the test fuels are used.

ENGINE COMPONENT DURABILITY AND MAINTENANCE

Changes in future fuel characteristics will likely have a pronounced effect on engine component durability and maintenance. The increasing flame temperature and luminosity that can be expected as fuel hydrogen content is reduced (1) can cause problems in cooling combustor liners and turbine vanes and blades. Changes in fuel volatility and chemical stability can be expected to increase carbon formation and deposition. And any increase in reactive trace constituents will certainly aggravate the erosion and corrosion problems. Each of these changes are considered in the following discussion.

Combustor Liner Temperature

The effective cooling of combustor liners is becoming more difficult because of the changing engine cycle conditions associated with high-pressure-ratio engines. The effect of increasing combustor inlet temperature on liner temperature is illustrated in Figure 12 (taken from ref. 8). The effect is almost linear and is probably caused by the increasing cooling-air temperature and the increasing flame temperature that would occur at a fixed primary-zone fuel-air ratio as inlet air temperature is increased. Another factor that can increase flame temperature and flame emissivity is combustor pressure. The effect of increasing combustor pressure on liner temperature is illustrated in Figure 13. Calculated liner temperatures are also shown in both Figures 12 and 13 and, in general, they are in reasonable agreement with both the shape and trend of the measured experimental temperature and pressure effects. However, the calculated absolute liner wall temperature levels are too high probably because total flame radiation cannot be accurately forecast. The sensitivity of liner wall temperatures to flame emissivity (luminosity) is strongly affected by the hydrogen-to-carbon ratio of the fuel (1). This effect is illustrated in Figure 14, where experimentally measured liner temperatures are plotted as a function of the hydrogen content in the fuel used for testing a can combustor (6) at two simulated engine operating conditions. The steeper slope of the measured liner temperatures at the cruise conditions suggests that the flame luminosity effect becomes more pronounced at the compressor discharge pressures associated with the cruise condition. The effect of combustor pressure on soot formation, and hence flame luminosity, is described in detail in reference 9.

In summary, there are several factors that could affect combustor liner temperatures in future aircraft engines. Increases in cycle pressure ratio that are being sought to improve engine efficiency are certainly going to require additional attention to the liner cooling problem. It is also apparent that reductions in the hydrogen content of future fuels will surely aggravate any problems associated with liner cooling.

Carbon Formation and Deposition

The combination of the inability to effectively atomize the fuel that is injected into a combustion chamber and a reduction in fuel hydrogen content can cause some rather dramatic carbon formation and deposition problems, as illustrated in Figure 15. Figure 15 shows carbon deposition that occurred in an experimental annular combustor for a low-pressure-ratio engine. Carbon deposition this severe is not prevalent in today's high-pressure-ratio engines. However, carbon formation could once again become a problem if fuel volatility and hydrogen content are significantly modified. The effect of both volatility and hydrogen-carbon ratio on carbon deposition is illustrated in Figure 16 (taken from ref. 11). The use of fuels with higher boiling ranges (e.g., diesel oil) and lower hydrogen-carbon ratios (higher aromatic content) would tend to increase carbon deposition. Because these effects are pressure and temperature dependent, the higher cycle temperature of most modern high-performance engines should reduce the probability that carbon formation and deposition as dramatic as that shown in Figure 15 would occur with the use of future fuels having low volatility and hydrogen content. However, some of the new low-pressure-ratio small engines used in remote-piloted vehicles (RPV's) could encounter rather serious problems when using fuels with relaxed volatility and hydrogen content specifications.

Carbon deposition and coking within fuel nozzles can cause problems in fuel atomization such as illustrated in Figure 17. The streaking effect that is shown in the spray pattern is most likely caused by deposits in the small fuel-nozzle passages that occurred due to thermal stability problems in the fuel. Poor fuel atomization can cause the carbon formation and deposition problems that were previously discussed and can also result in significant hot-streak and pattern-factor problems within the combustor.

Erosion, Corrosion, and Deposition

There are three principal factors that can cause problems within the hot section of an aircraft engine, particularly in the turbine: high combustion-exhaust-gas temperatures, unburned combustion products, and impurities in both the fuel and the air. All these factors can combine to produce an environmental attack on turbine materials (12), as shown schematically in Figure 18. Impurities such as sodium, chlorides, and sulphur can result in gaseous reactions, liquid deposition, and oxide fluxing, all of which can produce high-temperature oxidation and corrosion damage. Damage from liquid and solid deposits and fouling occurs because of calcium, potassium, and magnesium impurities within the fuel. Erosion damage can occur from the impact of liquid or solid particles such as carbon, ash, or dirt particles in the combustion gases.

The effect that the preceding damage forms can have on a turbine is illustrated schematically in Figure 19. Weight loss from erosion is estimated to occur in a nearly linear fashion with time as would the weight gain from deposition (fouling). Corrosion is the most severe form of environmental attack, and long-term loss in specific weight becomes disastrous. All of the factors illustrated in Figure 19 affect turbine life. Deposition and fouling can lessen the efficiency of turbine cooling by plugging film-cooling holes, as shown in Figure 20; and erosion and corrosion can cause material distress, as illustrated in Figure 21.

By combining the aforementioned "impurity"-related turbine life factors with the normal life-limiting factors of materials, a life-limiting picture of turbine components such as the one illustrated in Figure 22 can be constructed. This schematic representation illustrates how erosion and corrosion can drastically shorten turbine-component life beyond that which would normally be controlled by fatigue, creep, and material melting temperatures only. If the allowable limits of fuel impurities, such as sodium and sulfur, and of the fuel hydrogen content are relaxed in future fuels, the aforementioned effects may become significant problems.

ENGINE TECHNOLOGY NEEDS

The preceding sections of this paper describe several problems that may arise from the relaxing of fuel specifications for aircraft engines. The technology that will be needed to minimize or eliminate these problems is described in this section of the paper. Some critical research and development needs have been identified:

- Improved cooling techniques
- Reliable ignition and relight
- Reduced exhaust emissions
- Improved fuel injectors
- Prevention of carbon deposition
- Improved materials and coatings

Although it is not within the scope of this paper to discuss in detail the research and development needs in all these areas, technological advances currently being sought are presented and discussed.

Engine Performance

A variety of techniques can be considered to minimize potential ignition and relight problems. Heating the fuel to reduce its viscosity can be effective in improving fuel atomization. Primer or auxiliary fuel nozzles, designed for use during ignition and relight only, can also improve fuel atomization at engine starting conditions. Torch ignitors have been very effective in many military applications for high-altitude relight. All these techniques will add a degree of complexity to the engine and its fuel control. Therefore, simpler and more reliable techniques are surely going to be needed.

Several potential design concepts can be used to control exhaust emissions, a problem that may be aggravated by relaxed fuel specifications:

- Staged combustion
- Air-atomizing fuel injectors
- Intensive fuel-air mixing
- Lean combustion
- Fuel-air premixing
- Fuel prevaporization

In practice, a combination of many of these techniques could be used in any particular combustor concept. As an example, two recently evaluated advanced combustor concepts are shown by the cross-sectional schematics shown in Figure 23. Both the Vorbix and double-annular combustion concepts, which were evolved during the NASA Clean Combustor Program (13,14), incorporate fuel staging, air-atomizing fuel injectors, and lean combustion. The Vorbix combustor also uses intensive fuel-air mixing. Both combustor concepts substantially reduce all the gaseous exhaust emissions below the levels of the conventional engine combustors that they were designed to replace. The use of one stage (pilot) to reduce CO and HC emissions during idle and a second stage (main) to reduce these emissions during high-power operation proved to be very effective, as shown in Figure 24. Staged-combustor concepts such as these will be needed to minimize the impact of decreasing fuel hydrogen content or increasing fuel-bound-nitrogen content on aircraft engine exhaust emissions. Both concepts have gone through successful experimental engine testing and are strong candidates for future energy-conservative and environmentally acceptable engines.

If more dramatic reductions in exhaust emissions are are required (e.g., NO_x) combining techniques such as prevaporizing the fuel and premixing the fuel and air will allow combustion to occur at extremely low fuel-air ratios and thus will dramatically reduce flame temperatures. Successful development of prevaporizing-premixing techniques could provide additional decreases in NO_x emissions, such as those discussed in reference 15 and shown in Figure 25.

A variety of minor combustor modifications can be used to reduce CO and HC emissions without the major changes in combustor design shown in Figure 23. These modifications would deal mainly with improving fuel atomization and the distribution of air and fuel in the primary zone.

Although most of the aforementioned concepts have been or are being evolved to respond to environmental problems with current-specification jet fuels, they can certainly apply to future engines that would use relaxed-specification fuels. Therefore, continued exploration to define the capability of these concepts to control exhaust emissions from fuels with relaxed specifications is certainly going to be needed.

Engine Component Durability and Maintenance

Several potential design approaches can improve component durability and reduce maintenance requirements:

- Lean combustion techniques
- Advanced materials and coatings
- Advanced liner cooling techniques
- Improved structures

Lean combustion can reduce the effect of fuel hydrogen content on flame luminosity and therefore reduce liner temperature, as shown in Figure 26. A maximum liner temperature over 200° C lower than that of conventional combustors was realized when the two combustor concepts shown in Figure 23 were tested with a fuel having a hydrogen content of about 12 1/2 percent by weight. Another feature of the lean-combustion approach that is indicated by the results shown in Figure 26 is that the liner temperature appears to be insensitive to fuel hydrogen content. This insensitivity would be a significant advantage in future engines because a rather flexible fuel-hydrogen content specification could be used without compromising liner durability as affected by increasing liner temperatures.

Thermal-barrier coatings also offer the potential for reducing liner temperatures. A conventional can combustor with a thermal-barrier coating is shown in Figure 27 (taken from ref. 16). A zirconia ceramic coating was applied to the liner inner wall. The com-

bustor was tested over a range of conditions simulating engine takeoff and cruise; the resultant effect of the ceramic coating on the maximum liner temperature is shown in Figure 28. Significant reductions in maximum liner temperature were realized at both the cruise and takeoff conditions. Research and development of this and other advanced liner-cooling techniques, such as those shown in Figure 29, is certainly warranted.

The continued development of all the aforementioned approaches will surely be needed to maintain acceptable durability and maintenance characteristics of future engines using relaxed-specification fuels.

Erosion, Corrosion, and Deposition

Solving the problems of erosion, corrosion, and deposition on engine hot-section life will require many of the design techniques already described. Reducing combustor soot and carbon formation and minimizing the effect of such trace constituents as sulphur, potassium, and manganese must be actively pursued. Corrosion-resistant materials are being developed, and the use of coatings to protect the parent metal is also being evaluated (17). One example of how materials and coatings can affect the impact of corrosion on specific weight change is shown in Figure 30. Continued exploration in this area is certainly warranted, as well as the development of advanced turbine blade and vane cooling schemes that are less susceptible to plugging by deposits.

Many of the aforementioned research and development needs are being addressed in the NASA Fuels Technology Program, as well as in other U.S. Government and industry-sponsored programs. Presently, the main emphasis in the NASA program is on evaluating combustion and durability problems. However, because of the importance of all the problem areas discussed in this paper, problem definition and response to technological needs must be continuously reviewed. A comprehensive data base will surely be needed if we are to optimize the trade-off between advanced technology development and fuel specification relaxation for future aircraft applications.

AIRCRAFT ENGINE FUEL SYSTEMS

The fuel properties that are most likely to cause problems in aircraft engine fuel systems are those that affect fuel thermal stability, flowability, and pumpability and fuel-system material compatibility. These factors are principally affected by the fuel-bound-nitrogen and hydrogen content, freezing point, and aromatic content of the fuel. Another factor of concern in fuel systems is the effect of fuel volatility on safety. Since the forecasted trend in future fuels is toward a less volatile fuel, rather than a more volatile fuel that would present safety hazards, changes in potential safety problems are not expected and therefore are not discussed in this paper.

Thermal Stability and Deposition

Increasing fuel-bound-nitrogen content can result in a less thermally stable fuel. A similar effect is also noted for reducing fuel hydrogen content. The use of fuel as a heat sink in most aircraft fuel systems results in a rise in fuel temperature. If the fuel temperature approaches or exceeds the "breakpoint" of the fuel, deposits may form in the heat-exchanger passages and a loss in heat-transfer effectiveness can occur. (Fuel breakpoint temperature is discussed in ref. 1.) In the extreme, these deposits can become severe enough to produce flow restrictions in the fuel passages, thereby increasing the pressure drop. Fuel nozzles are also susceptible to this potential problem. One test that is commonly used to measure the thermal stability of the fuel is the JFTOT technique (1). As an example, a fuel that was derived from shale oil and refined to two different fuel-bound-nitrogen content levels was exposed to this test and the results are shown in Figure 31. As illustrated, the deposits that were formed within the tube were much more severe for the fuel with high fuel-bound-nitrogen content when both fuels were heated to the same temperature (e.g., 260° C).

Many factors are involved in the formation of fuel-system deposits. Several of the principal ones that have been identified are:

- Fuel properties
- Engine-cycle pressure ratio
- Flight duration
- Fuel contamination
- Surface material
- Fuel oxygen content
- Fuel additives

Even though fuel properties (i.e., fuel hydrogen and fuel-bound-nitrogen contents) is only one of the many factors involved, it is the one factor that will most likely be affected by any relaxation of fuel specifications for future aircraft engines.

Fuel Pumpability and Flowability

At the freeze point, a fuel begins to enter a semisolid state, which can have an adverse effect on its pumpability and flowability. For example, a semisolid fuel can severely block a screen filter, as illustrated in Figure 32. Any blockage of this magnitude in an aircraft fuel system could have disastrous consequences. Hence, maintaining fuel temperature at a safe margin above its freeze point is an absolute necessity. Therefore, any increases in fuel freeze point that could occur from relaxing the specifications of future fuels must be carefully considered.

Many factors must be considered in evaluating the minimum allowable fuel-tank temperature, such as flight routes, altitude, and duration and the initial fuel temperature. The effect that flight routes can have on fuel temperature is illustrated in Figure 33, where the average of the recorded in-flight fuel temperatures of a large number of aircraft is plotted as a function of the percentage of flight time that the fuel was above the minimum temperature recorded during the flight. The average fuel temperature data for each of three different routes, as documented by the International Air Transport Association, are shown. The North Atlantic and North Pole routes had fuel temperatures below -30° C about 20 percent of the time, but the Europe-to-South-America route had fuel temperatures below -30° C only about 2 percent of the time. An example of the calculated effect of both flight duration and initial fuel temperature on the fuel temperature for a long-range flight of 9300 km is illustrated in Figure 34. The procedures involved in this calculation are described in reference 18. After about 6 hours of flight, the calculations indicate that fuel temperature would reach about -40° C regardless of the initial temperature. This effect of initial fuel temperature could allow a higher-freeze-point fuel to be used for short-duration flights, but it would probably not provide any substantial benefit on typical long-duration flights.

Since the "candidate" broad-specification fuel described in reference 1 has a freeze point of about -29° C, some form of fuel heating will probably be required to prevent fuel pumpability and flowability problems in long-range aircraft using this fuel. A calculated projection of the percent of flights that would require fuel heating as a function of season, flight duration (mission), and fuel freeze point is shown in Table I. The analysis used to arrive at the data shown in Table I is discussed in detail in reference 19. Based on this analysis, the need for fuel-tank heating would be very minimal for the -29° C freeze-point fuel, but increasing the freeze point to -19° C would require heating on all flights at all times of the year. From these freeze-point considerations only, it would appear that a fuel with a relaxed fuel-freeze-point specification of -29° C (current value, -40° C) may be acceptable for aircraft use if fuel heating can be provided for selected flights.

Material Compatibility

One concern in aircraft fuel-system materials that could be affected by relaxing fuel specifications is the impact that increasing aromatic content may have on the elasticity of elastomer compound and sealants. This effect is shown in Figure 35. For an exposure time of 4 hours, the elasticity ratio f_ε/f_0 of a butadiene acrylonitrile rubber elastomer decreased from about 0.7 to 0.15 when the aromatic content of the fuel that it was immersed in was increased from 20 to 60 percent. The elasticity ratio f_ε/f_0 is described in reference 19 where f_ε is defined as the measured stress relaxation after exposure and f_0 before exposure. The loss in elasticity shown in Figure 35(a) may affect the ability of this elastomer material to be effective in applications such O-ring seals. A similar, although not quite as pronounced, effect is shown in Figure 35(b) for a typical sealant material. It should be noted here that many elastomer compounds can be and are tailored to specific fuel properties so that these affects would be minimized for a given fuel in a given application. However, for aircraft fuel systems that must operate with fuels having a wide range in aromatic content, the material compatibility problems illustrated could become significant.

AIRCRAFT FUEL-SYSTEM TECHNOLOGY NEEDS

The preceding section describes some of the fuel-system problems that can be anticipated from the relaxing of fuel specifications. The technologies that must be developed to minimize or eliminate these problems are discussed in this section. Some of the critical fuel-system areas where continued research and technology efforts are needed are:

- Fuel-tank heating
- Fuel manifold and fuel injection fouling
- Elastometers and sealants
- Ground handling

Although the need to improve ground handling techniques for storing and loading higher-freeze-point fuels is recognized, it is not discussed in this paper because we are prinicipally addressing potential propulsion-system problems. The effects of fuel properties on fuel manifold and injector fouling and on elastometers and sealants still needs considerable evaluation before the technological needs can be clearly defined and pursued. Therefore, we will concentrate on those advances in technology that are needed to solve the fuel pumpability and flowability problems that could occur when using fuels with freeze points higher than those currently specified.

The calculated effect of fuel-tank heating on fuel temperature as a function of flight time for a typical long-range, wide-bodied jet aircraft is shown in Figure 36 (taken from ref. 19). Two levels of constant heat input to the fuel were used in the computation. For the entire 9300-km mission, a heat input of 3700 kJ/min per fuel tank would be needed to maintain the fuel temperature above a freeze point of -29° C, and 6500 kJ/min per fuel tank would be needed to maintain the fuel temperature above -18° C freeze point. Since the fuel temperature stays above the -29° C freeze point during the first several hours of the mission, no fuel heating would be needed during this portion of the mission for a fuel having this relaxed freeze-point specification. Therefore, from an economic standpoint, it would seem reasonable to consider the use of selective heating as required rather than the continuous heating that was used to calculate the characteristics shown in Figure 36. The effectiveness of this approach is illustrated in Figure 37, where calculated fuel temperatures are plotted as a function of flight time for a 9300-km mission of a typical wide-bodied jet aircraft. The calculated characteristics shown for the various tank locations also indicate that it would probably not be necessary to apply heat during the early portion of the flight. Using selective fuel-tank heating would certainly reduce the total heat input needed to heat the fuel during the entire mission.

Another technique that could be used to reduce the total heat input needed for a mission would be to insulate the fuel tanks. An example of how tank insulation thickness could reduce heat input is shown in Figure 38 for a 9300-km mission of a typical wide-bodied jet aircraft. Increasing tank insulation from zero (value assumed in the Fig. 36 calculations) to a 2.5-cm thickness would result in a factor-of-4 reduction in the heat input needed to maintain the fuel above -29° C. The application of this much insulation would produce an aircraft weight penalty that would have to be compared with the savings in heat input before such a technique could be considered.

An example of aircraft heat sources that could be used to provide the needed heat input to the fuel tank is illustrated in Figure 39. The use of the cabin air-conditioning and lubricating-oil heat exchangers would require minor modifications to the aircraft and fuel system and could be implemented with a relatively low risk. The use of fuel boost-pump recirculation and an engine-driven electric heat exchanger would probably require minor-to-moderate modifications. The use of compressor air bleed would require moderate modifications and developmental risks. And the use of a tailpipe heat exchanger would require the most difficult and highest risk modifications. The calculated increases in aircraft weight for a typical wide-bodied jet aircraft and the resultant fuel penalties associated with using these fuel heat sources are given in Table II. In the minor-to-moderate class of modification, the lubricating-oil heat exchanger and the engine-driven electric heater appear to represent a reasonable approach from a combined heat input and fuel penalty consideration. Neither the air-conditioning-system heat exchanger nor fuel boost-pump recirculation would provide a satisfactory heat input rate (Fig. 37). Compressor air bleed would result in a very high fuel penalty. And the tailpipe heat exchanger would have a very high development risk, which certainly reduces its attractiveness even though its successful application would result in the lowest fuel penalty for a given required heat input rate (e.g., 6500 kJ/min).

Although research into all these heat-input techniques should and will be continued, the results of the present studies indicate that the engine-driven electric heater may offer a reasonable trade-off between heat input rate and fuel penalty. This technique may also have an additional advantage over the others because auxiliary ground power could be used for tank heating while the aircraft is on the ground with the engines off. This could be important for operations in extremely cold climates. The very large fuel penalty associated with the weight of effective tank insulation certainly minimizes the attractiveness of this approach. Although these results were based on calculations and experimental verification is still needed, they do help to focus the research and development needed to provide the technology that will allow fuel freeze-point specifications to be relaxed.

CONCLUDING REMARKS

The objective of this paper was not to discuss or debate the advisability of using relaxed fuel specifications for future aircraft applications. Rather, the intent was to point out and discuss some of the problems that could arise if these fuels must be used and to illustrate the advances in engine and fuel-system technology that may be needed for these fuels to be acceptable in future aircraft. In this context, then, it has been stated that the principal fuel properties of concern are those related to increased aromatic compounds (lower fuel hydrogen content), increased fuel-bound-nitrogen compounds, higher boiling points (reduce volatility), and higher freeze points. All these properties are associated with the relaxation in fuel specifications that may be needed to provide a larger supply of petroleum-derived jet aircraft fuels and to reduce the degree of refining needed to convert oil-shale- and coal-derived crude oils into acceptable jet aircraft fuels in the future. In addition to these fuel properties, increases in such trace constituents as vanadium and potassium may also be of concern. Techniques such as fuel heating may also be important.

Potential adverse fuel property effects on engine performance are related to probable changes in ignition and relight limits and in exhaust-gas emission levels. Counteracting both of these effects will require advanced combustor technology such as improved or auxiliary fuel atomizers, better fuel-air distribution, and mixing and lean combustion

techniques. Counteracting problems related to component durability and maintenance will require such advanced technology as improved fuel atomizers, lean combustion techniques, thermal-barrier coatings, and new materials. Solving problems in aircraft fuel systems will require fuel-tank heating techniques and "tailored" elastometer materials. Even though preliminary evaluations of several of these technological advances have been encouraging, considerable research and development is still needed to make them acceptable in production engines and aircraft fuel systems. Furthermore, the ability to cope with several other problems, such as those caused by variations in thermal stability and by trace constituents, has not been demonstrated to even an acceptable experimental level at the present time. The factors that contribute to variations in thermal and chemical stability are not well understood and much more research is needed. Turbine erosion and corrosion problems may be somewhat relieved by using coatings, but considerable research is needed to fully understand all the factors that contribute to these problems.

Because of the many unknowns that must still be explored and explained through research and development efforts, it is apparent that these efforts should proceed at an orderly and timely pace. Although it is unlikely that aircraft will have to operate with the wide variation in fuel properties discussed in this paper, a sound and complete technological data base must be developed as soon as possible if the aircraft industry is to have any impact on setting acceptable variations in the specifications of future aircraft fuels. It is none too soon to start developing this data base since trade-offs will have to be made to determine the optimum choice between the cost and difficulty of developing advanced engine and fuel-system technology and the economic advantages to be gained by reducing the degree of refining needed to produce current-specification fuels from projected future fuel feedstocks.

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TABLE I. - UTILIZATION OF HEATING SYSTEMS (FROM REF. 19)

Mission length, km	Winter months		Summer months	
	-19° C fuel	-29° C fuel	-19° C fuel	-29° C fuel
	Flights predicted to use fuel heating systems, percent of total			
3700	53	0	45	0
5600	59	.1	50	
9100	73	5.3	59	
Combined utilization	62	1.8	52	

TABLE II. - COMPARISON OF POSSIBLE FUEL HEAT SOURCES

	Maximum heating rate per tank, kJ/min	Weight increase, kg	Fuel penalty, percent
Air conditioning system	2200	140	0
Lubricating-oil heat exchanger	4500	140	~.4
Fuel boost-pump recirculation	2100	140	~.4
Compressor air bleed	6500	300	3.9
Engine-drive electric heater	6500	450	.5
Tail-pipe heat exchanger	6500	250	.1
Insulation - 2.5 cm thick	----	5900	14.6
Equivalent heating by combustion	6500	----	.4

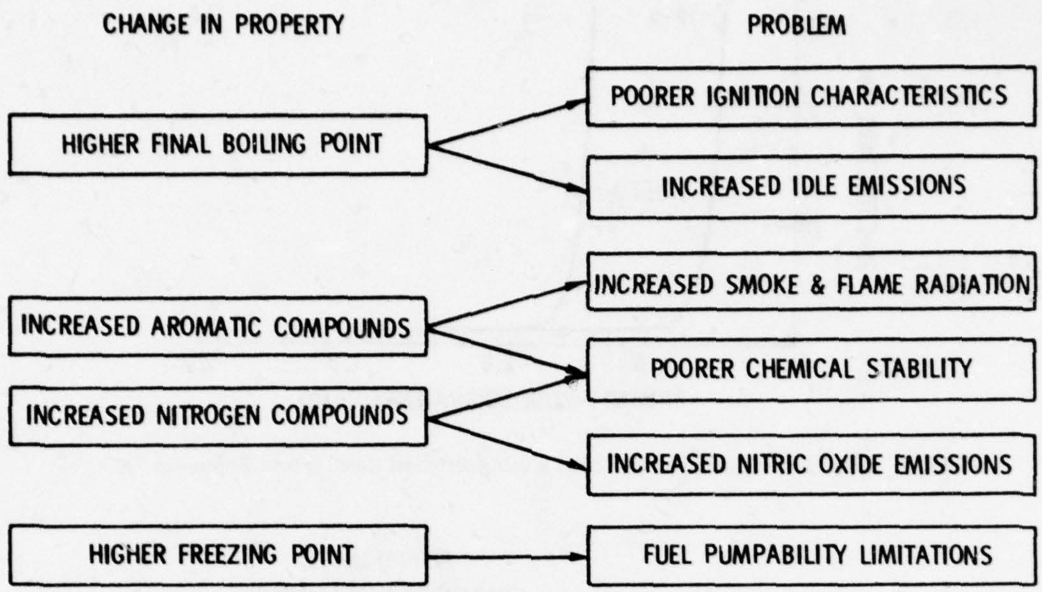

Fig.1 Potential problems from relaxing jet fuel specifications

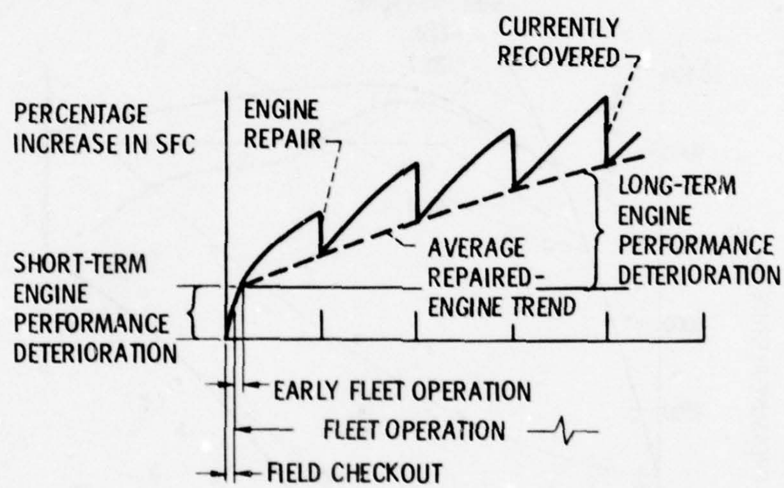

Fig.2 Specific-fuel-consumption performance deterioration trends for typical engine. (From Reference 4)

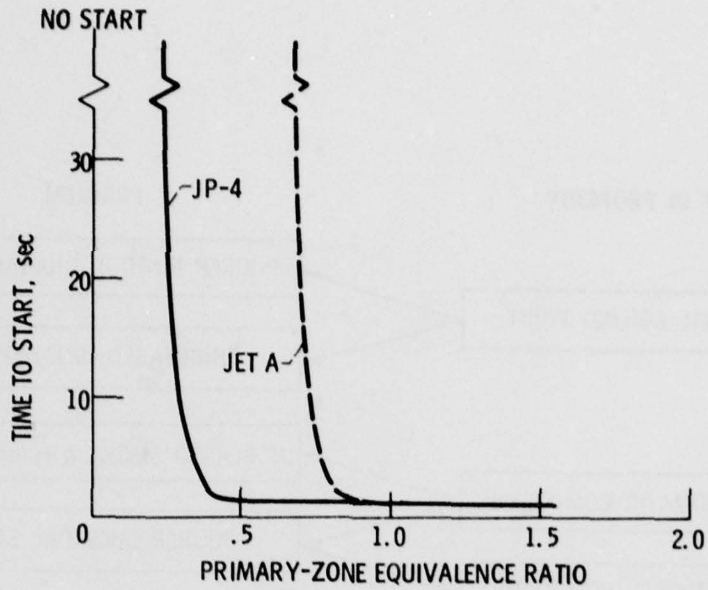

Fig.3 Combustor ignition characteristics using different fuels. (From Reference 5)

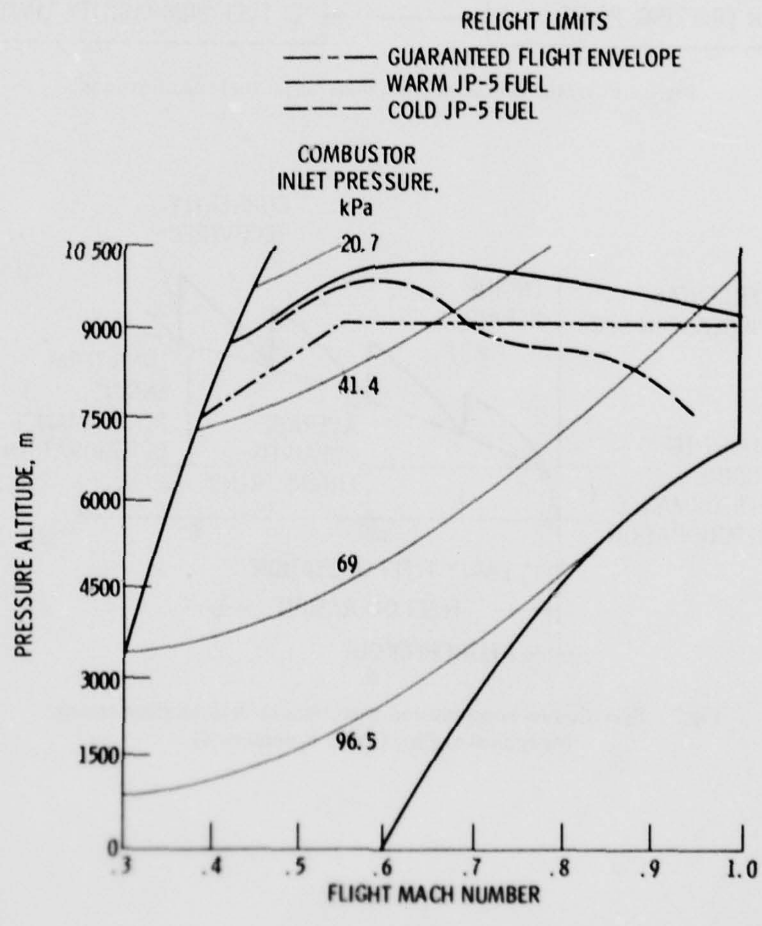

Fig.4 Altitude relight limits of a conventional annular combustor

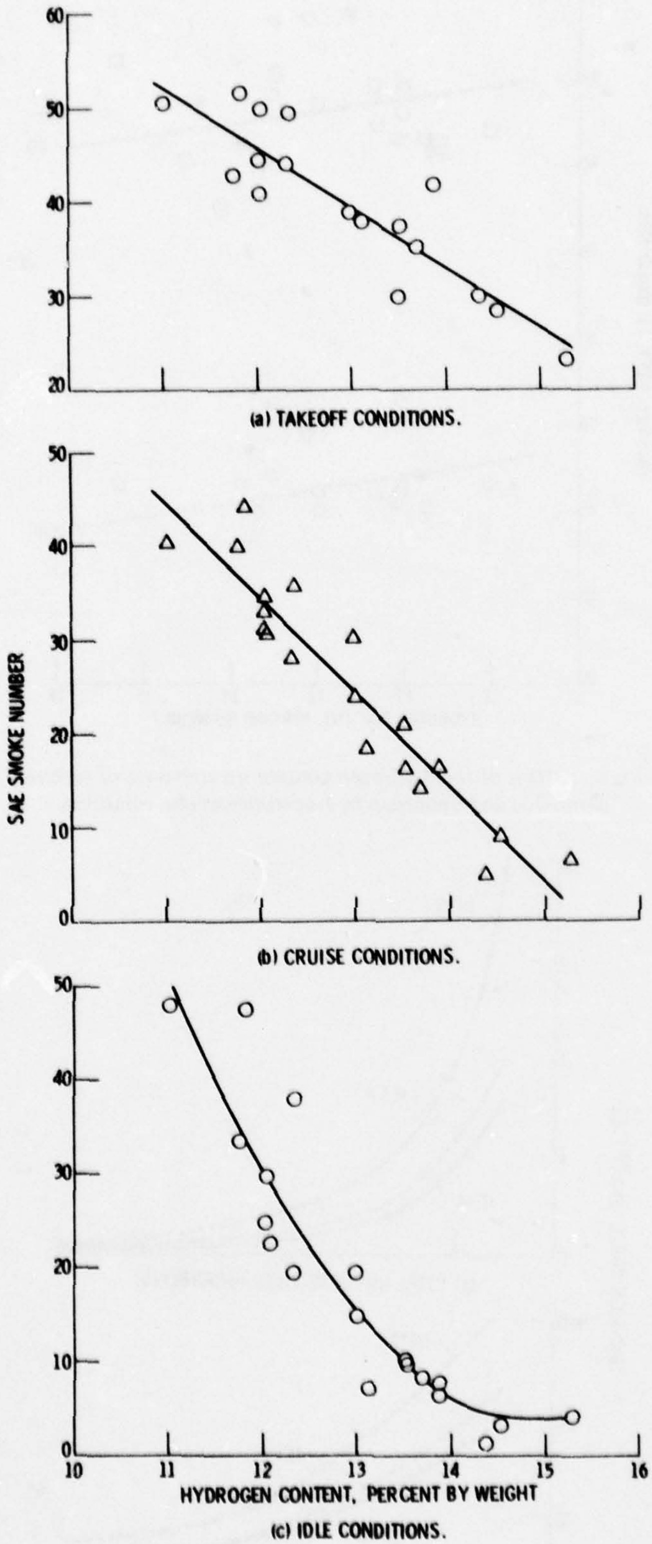

Fig.5 Effect of fuel hydrogen content on smoke number. (From Reference 6)

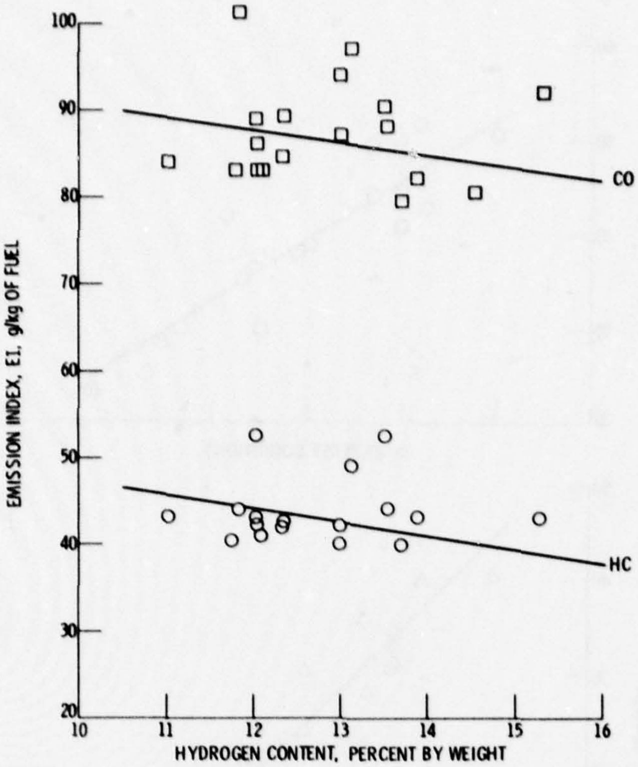

Fig.6 Effect of fuel hydrogen content on emissions of carbon monoxide and unburned hydrocarbons at idle condition

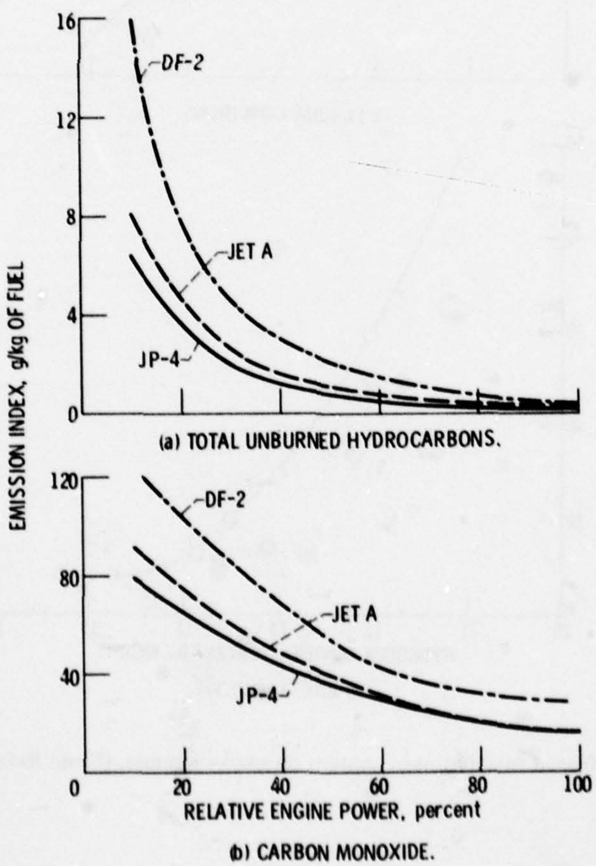

Fig.7 Effect of engine power setting on exhaust emissions of total hydrocarbons and carbon monoxide. (From Reference 5)

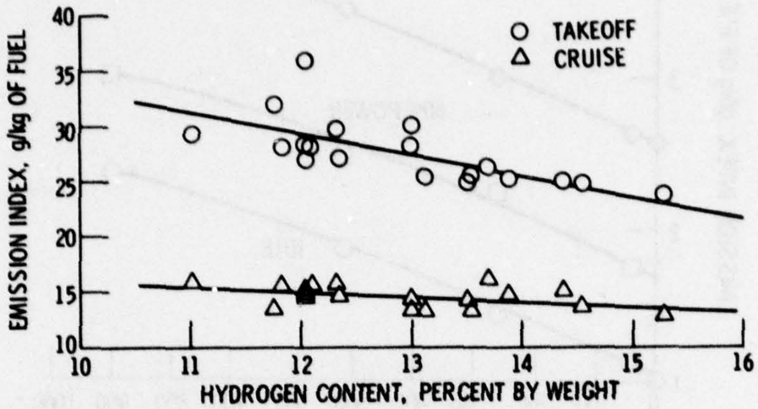

Fig.8 Effect of fuel hydrogen content on emissions of nitrogen oxides at takeoff and cruise conditions. (From Reference 6)

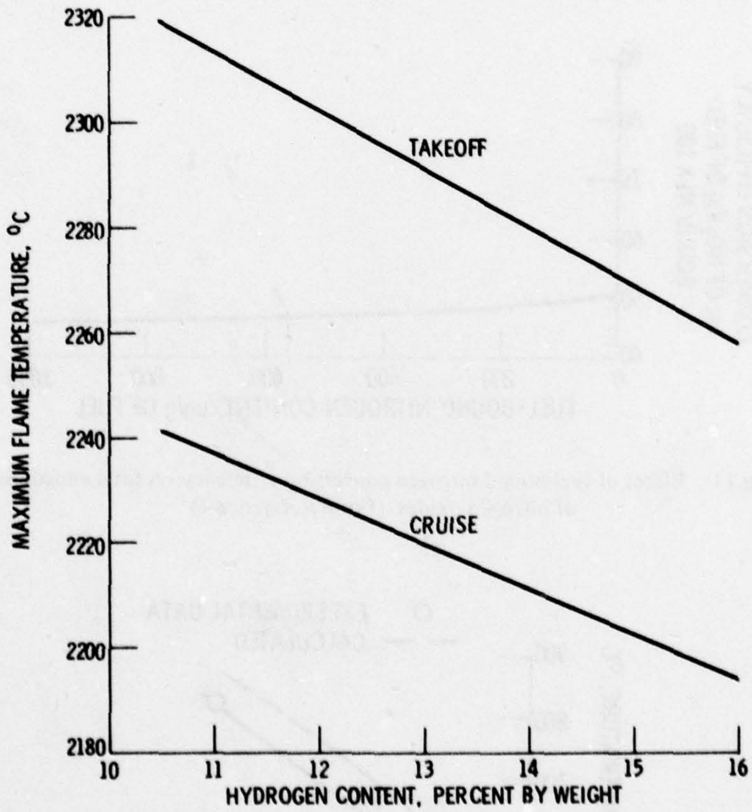

Fig.9 Effect of fuel hydrogen content on maximum flame temperature

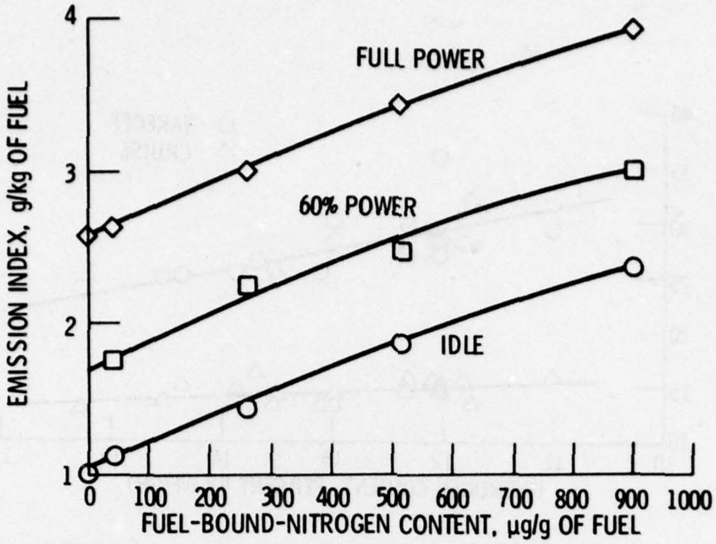

Fig.10 Effect of fuel-bound-nitrogen content on total emissions of nitrogen oxides. (From Reference 7)

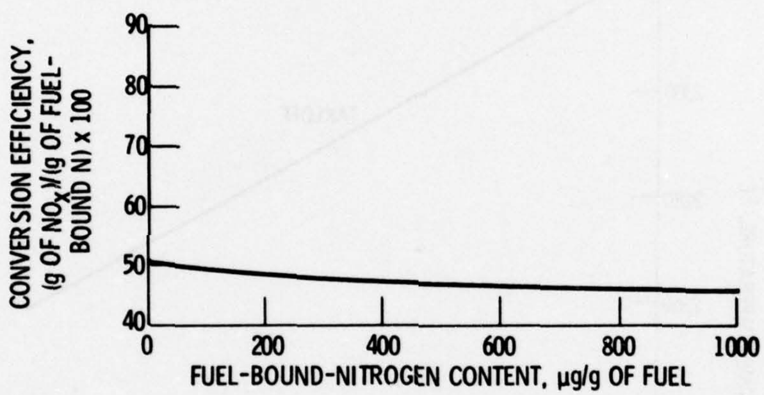

Fig.11 Effect of fuel-bound-nitrogen conversion efficiency on total emissions of nitrogen oxides. (From Reference 7)

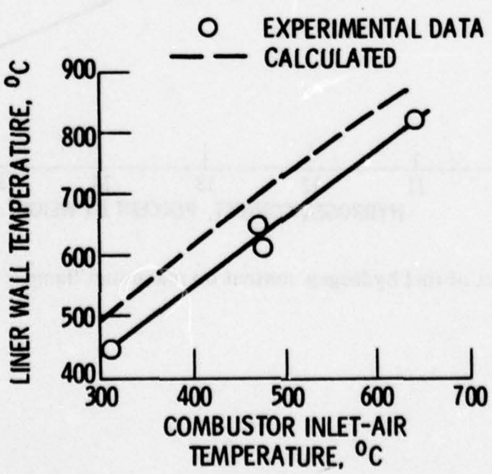

Fig.12. Comparison of experimental and calculated liner wall temperatures over a range of inlet-air temperatures

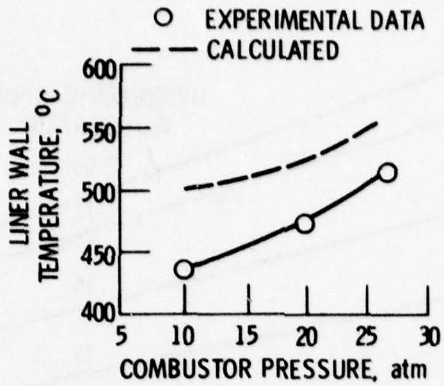

Fig.13 Comparison of experimental and calculated liner wall temperatures over a range of inlet-air pressures

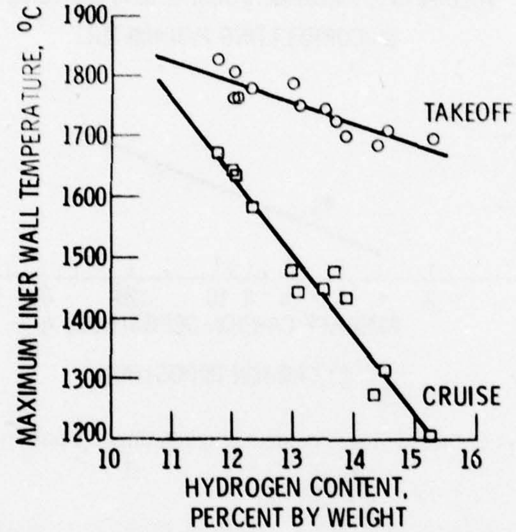

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Fig.14 Effect of fuel hydrogen content on maximum combustor liner wall temperature

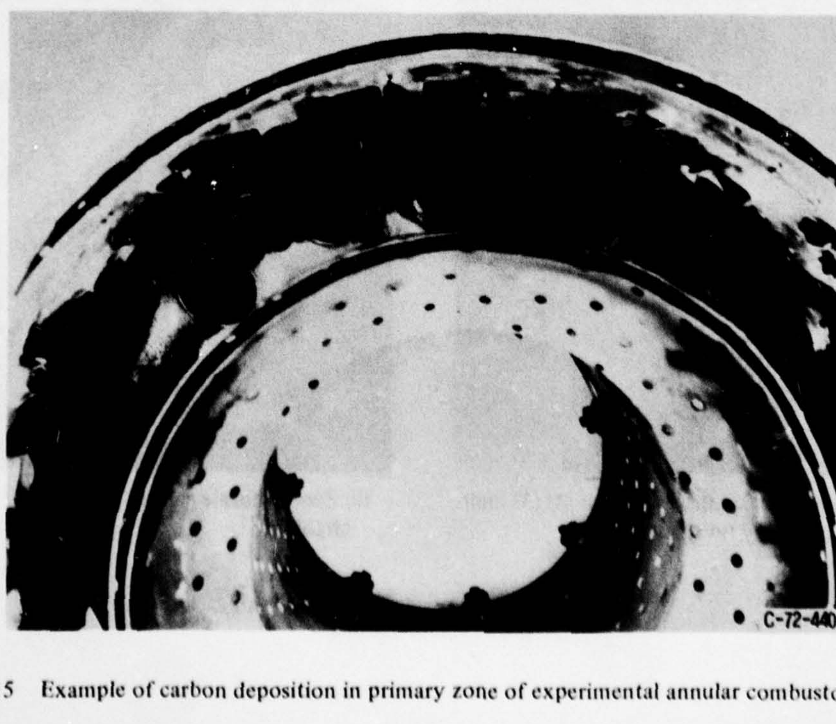


Fig.15 Example of carbon deposition in primary zone of experimental annular combustor

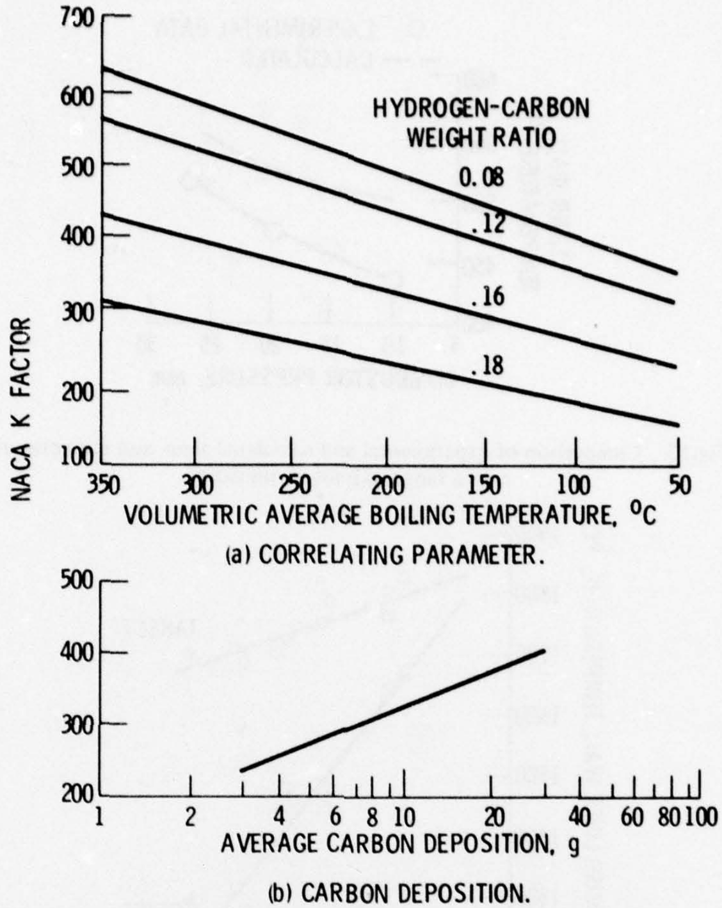
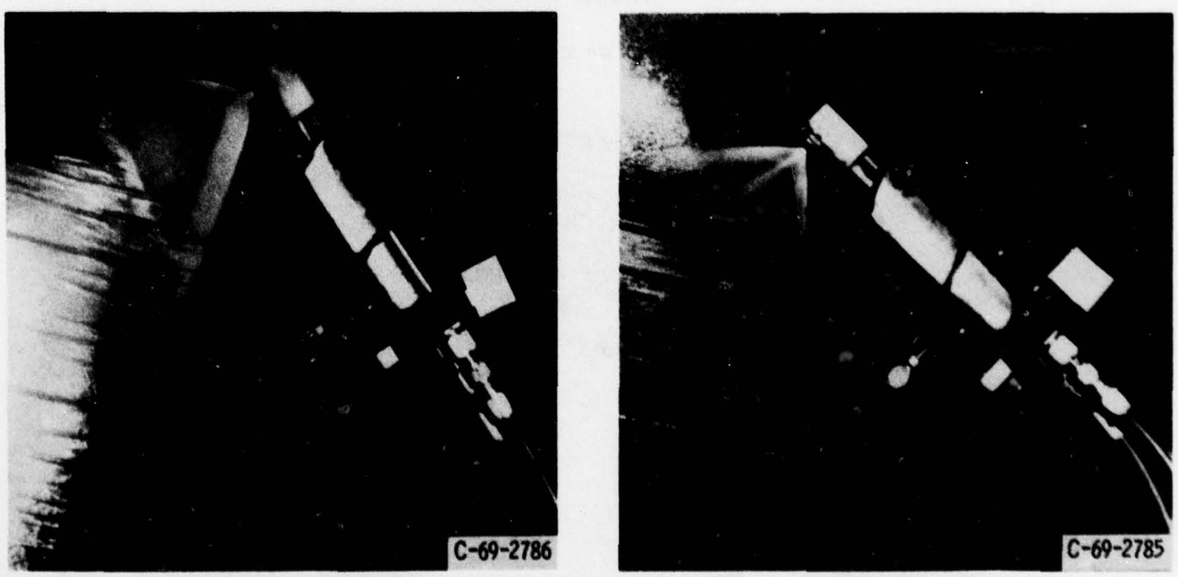


Fig.16 Effect of fuel hydrogen content and volatility on carbon deposition



(a) Zone 1 secondary nozzle flowing at 500 psi (33 atm) and showing essentially no streaking.

(b) Zone 1 nozzle demonstrating moderate amount of streaking.

Fig.17 Fuel nozzle spray patterns

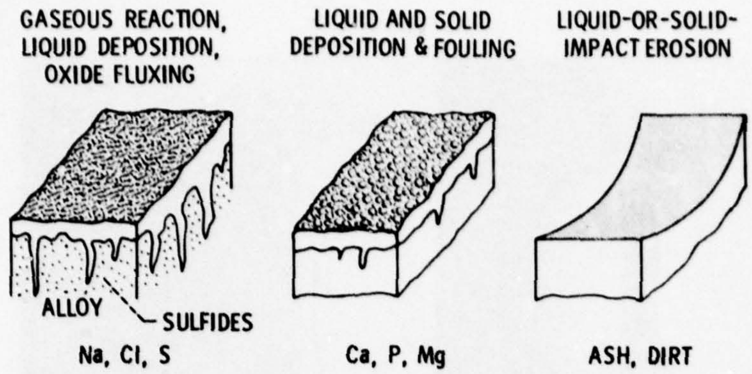


Fig.18 Schematic representations of environmental attack

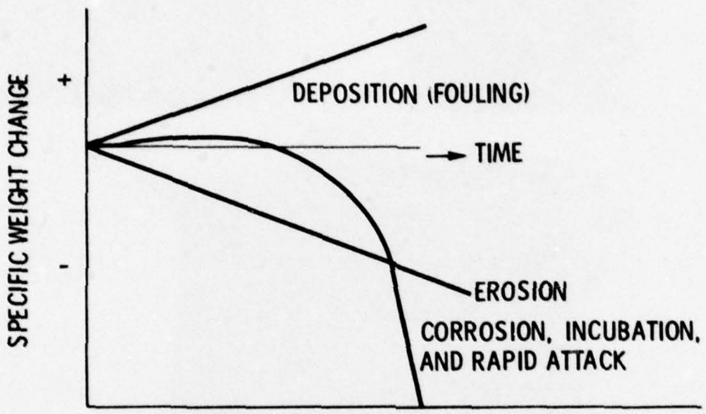


Fig.19 Specific weight changes for three modes of "impurity" – associated environmental degradation

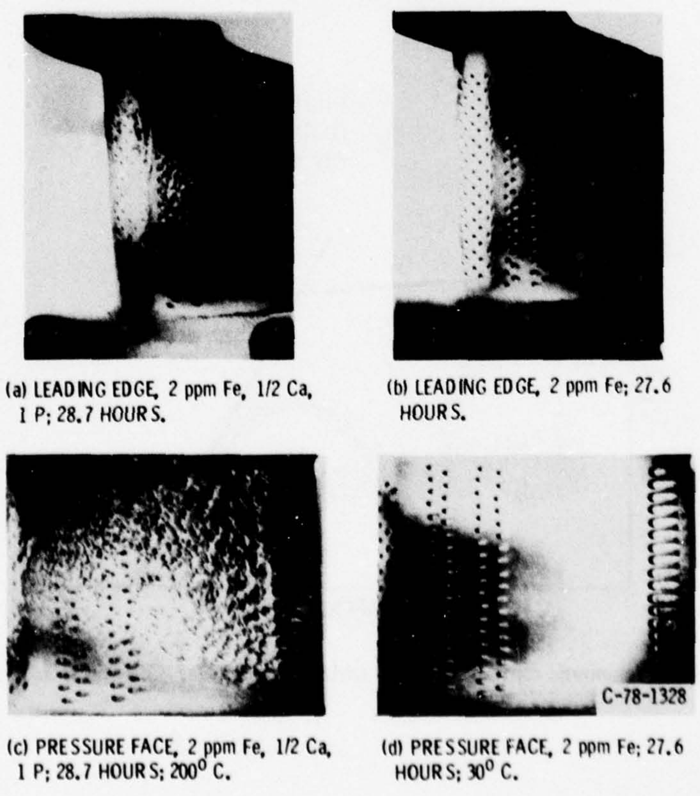


Fig.20 Examples of deposits and cooling-hole plugging on turbine vane

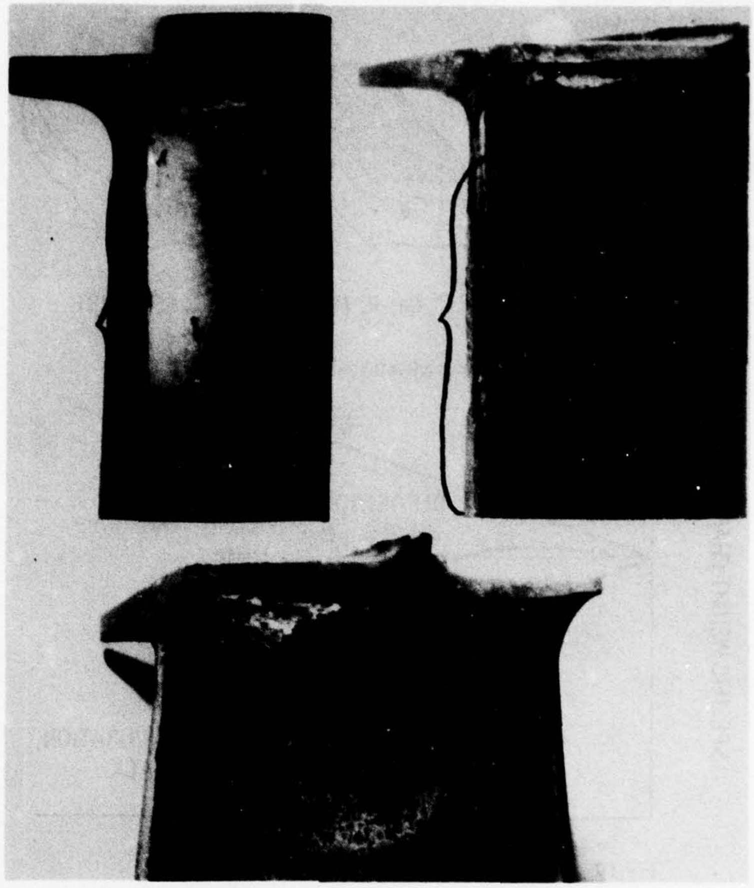


Fig.21 Examples of typical erosion and corrosion distress on turbine blade

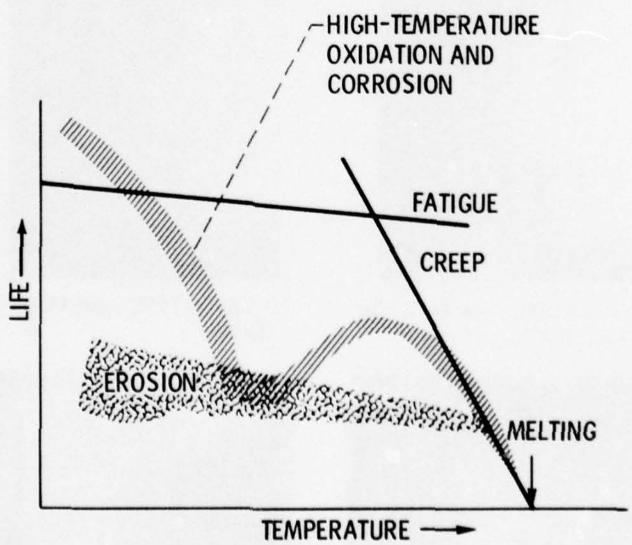
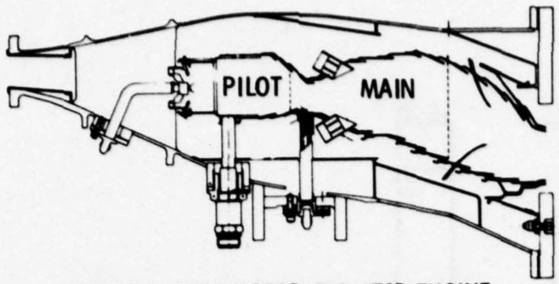
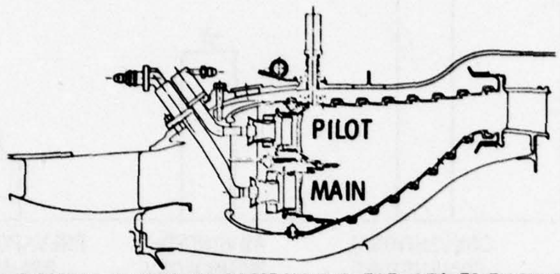


Fig.22 Schematic representation of turbine-component life-limiting factors



(a) VORBIX COMBUSTOR FOR JT9D ENGINE.



(b) DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE.

Fig.23 Combustor design concepts from NASA Experimental Clean Combustor Program

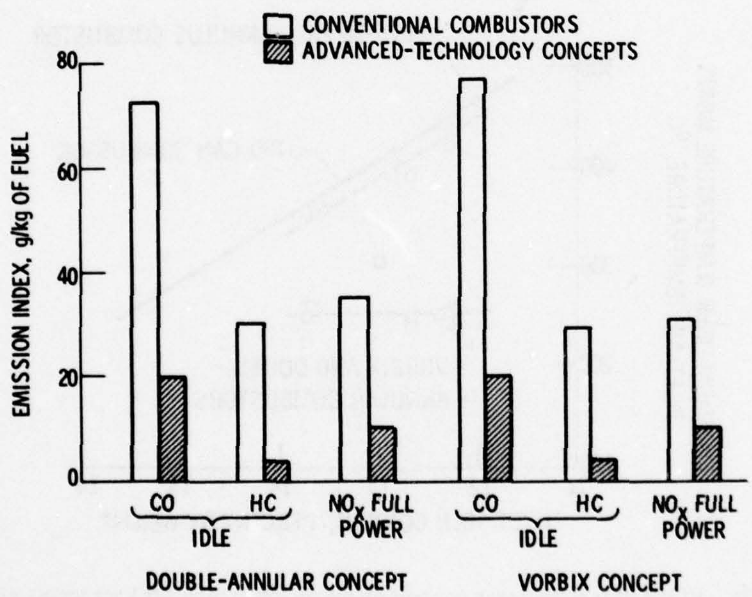


Fig.24 Emission reduction capability of selected advanced-technology combustor concepts

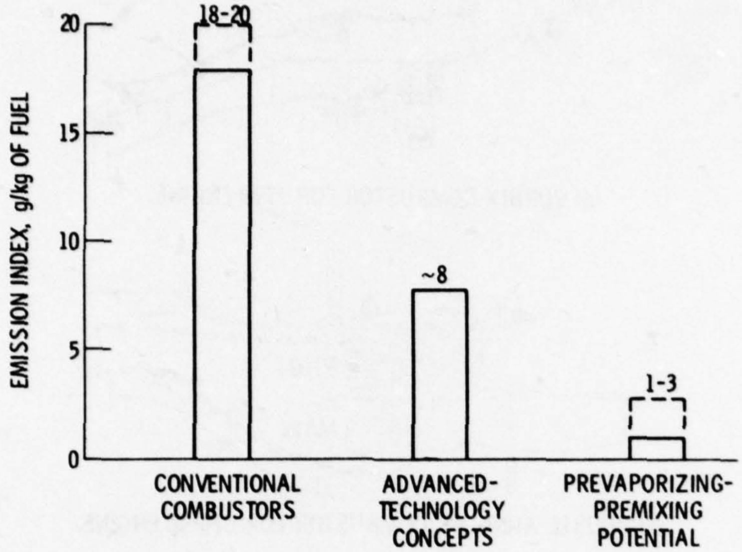


Fig.25 Progress in high-altitude, subsonic-cruise NO_x emission reduction

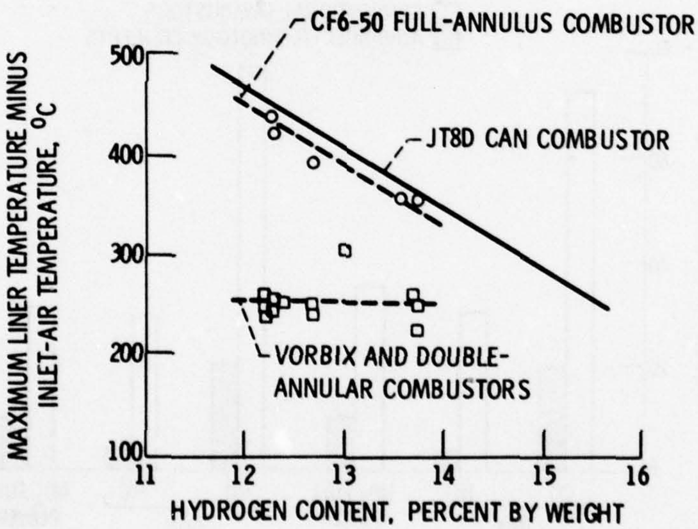


Fig.26 Effect of fuel hydrogen content on maximum combustor liner temperature

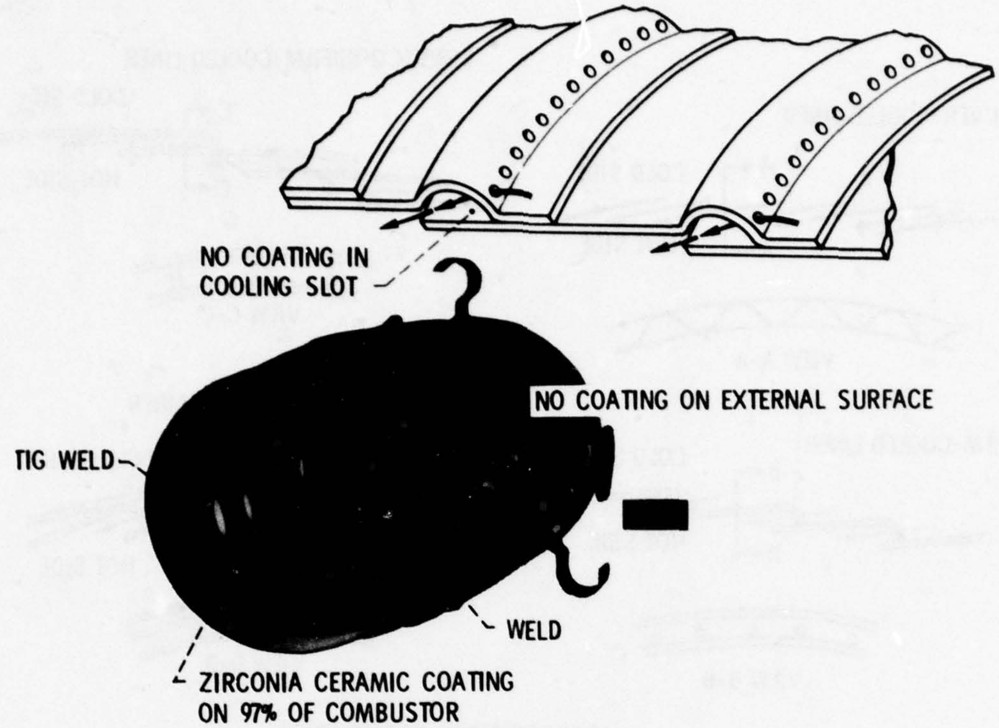


Fig.27 Thermal-barrier-coated combustor

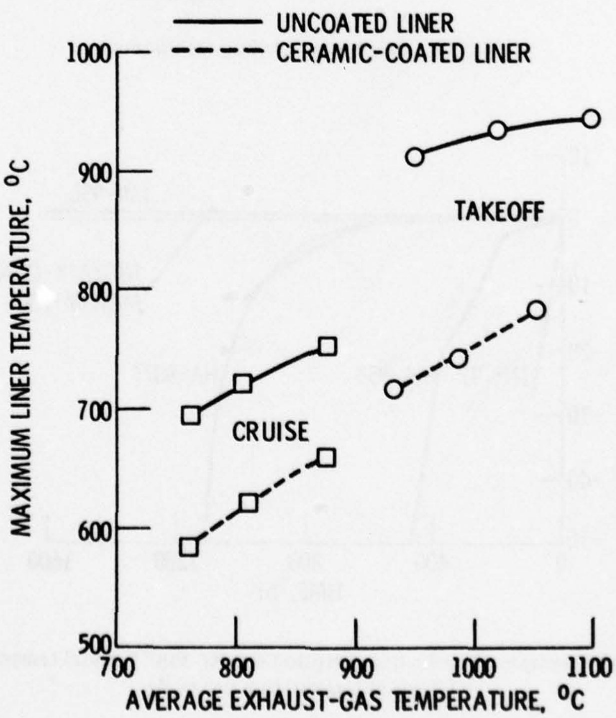


Fig.28 Effect of ceramic coating on maximum liner temperature

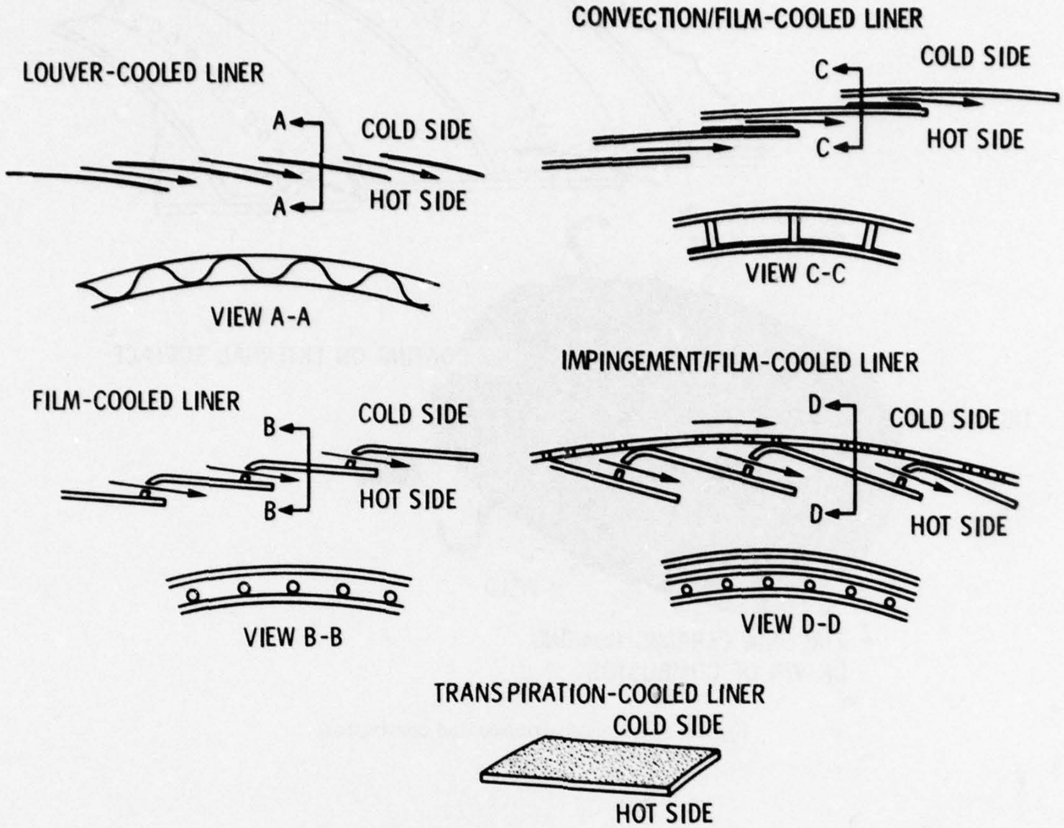


Fig.29 Combustor cooling techniques

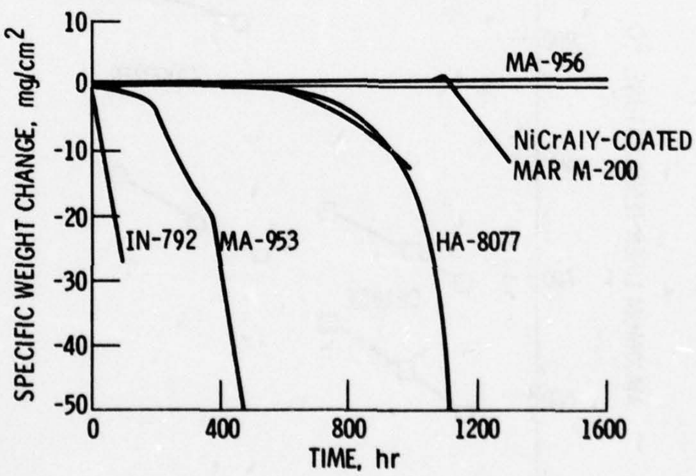


Fig.30 Example of cyclic hot-corrosion results: 900°C metal temperature; 1 hour at temperature per cycle

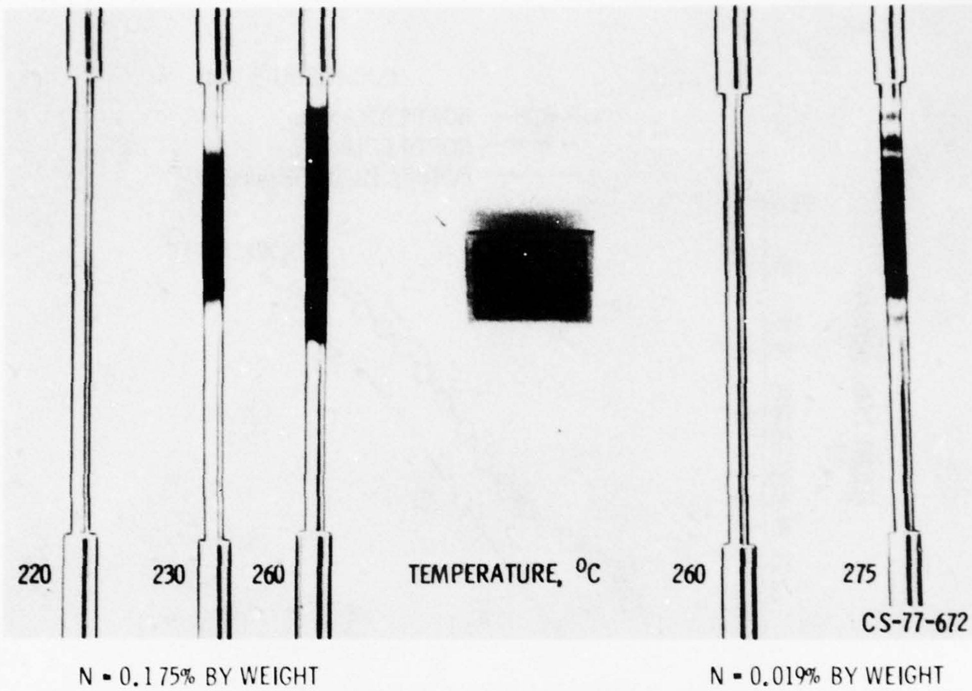


Fig.31 Thermal stability of shale fuels

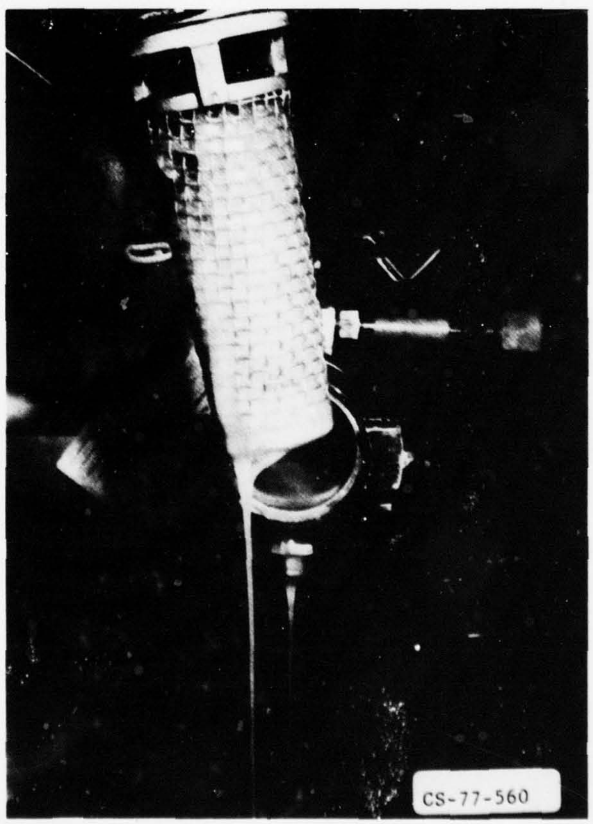


Fig.32 Screen blockage by semisolid fuel

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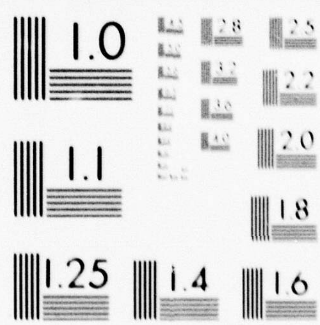

MICROCOPY RESOLUTION TEST CHART

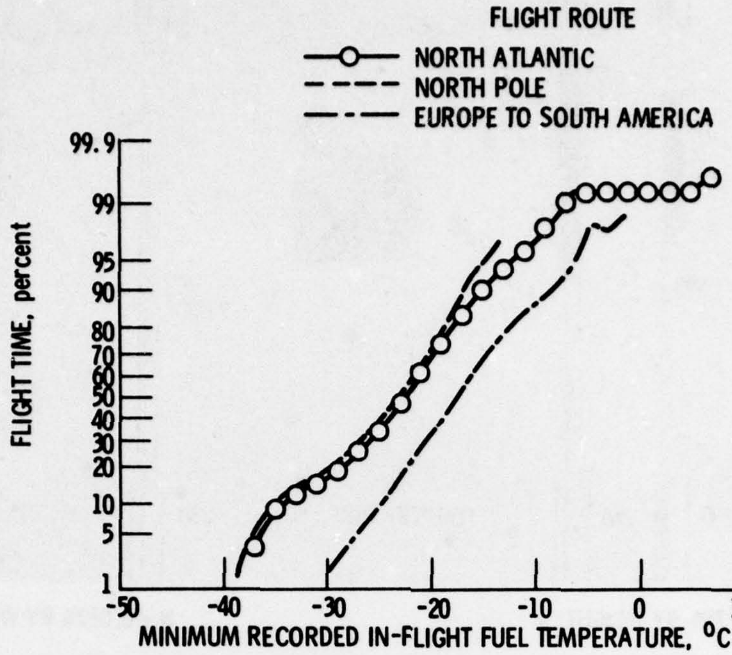

Fig.33 Relationship between flight time and measured average fuel temperature for various flight routes. (From Reference 18)

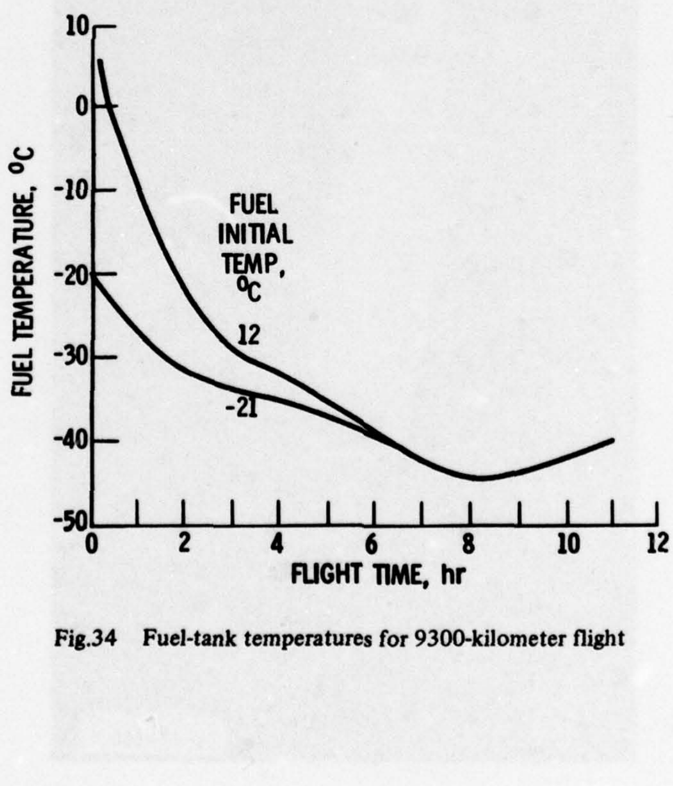

Fig.34 Fuel-tank temperatures for 9300-kilometer flight

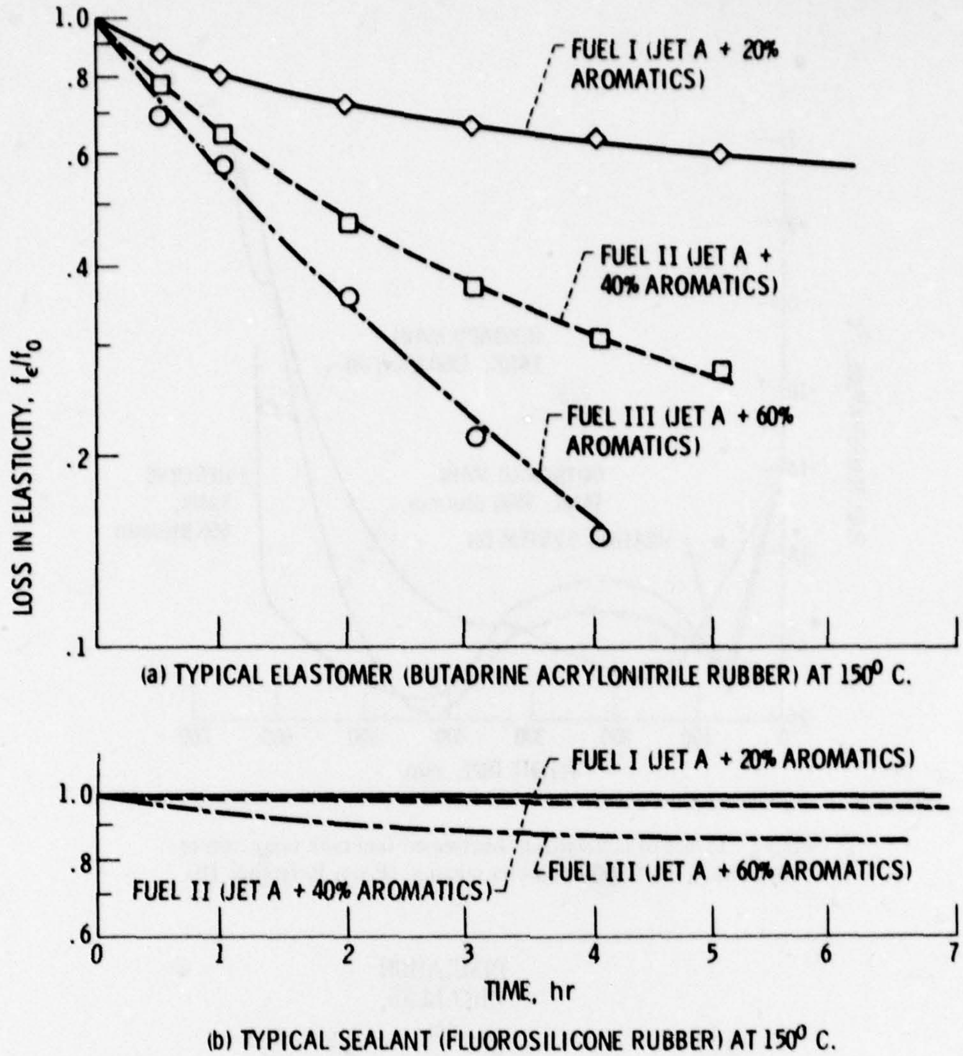

Fig.35 Effect of various fuels on material elasticity. (From Reference 20)

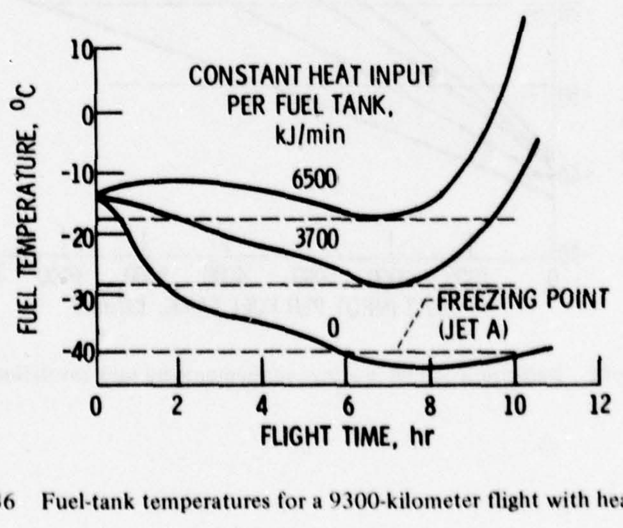

Fig.36 Fuel-tank temperatures for a 9300-kilometer flight with heating

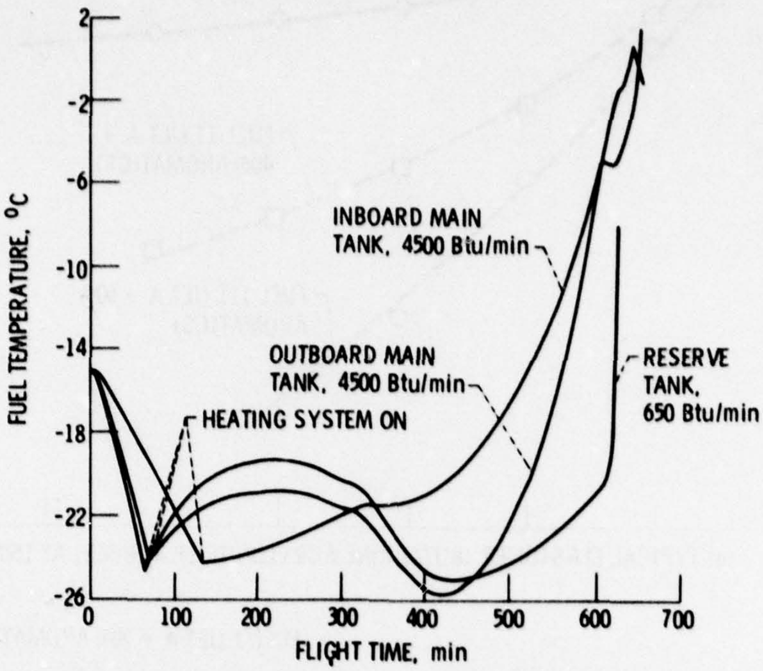

Fig.37 Effect of intermittent heating on fuel tank temperature. Wide-body jet; 9300-kilometer mission. (From Reference 18)

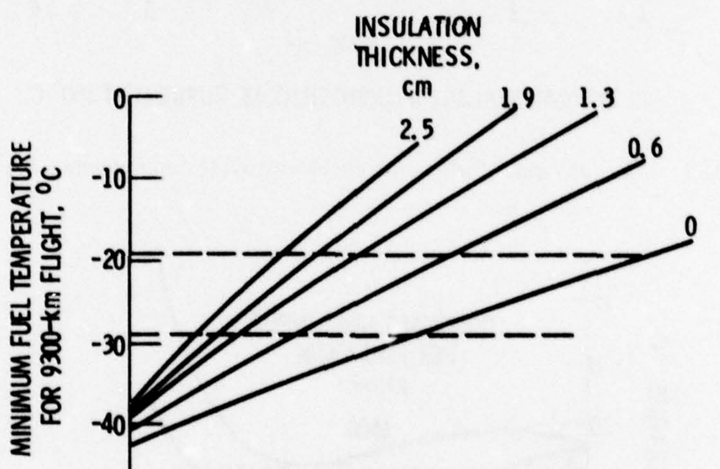

Fig.38 Reduction of fuel heating requirements by tank insulation

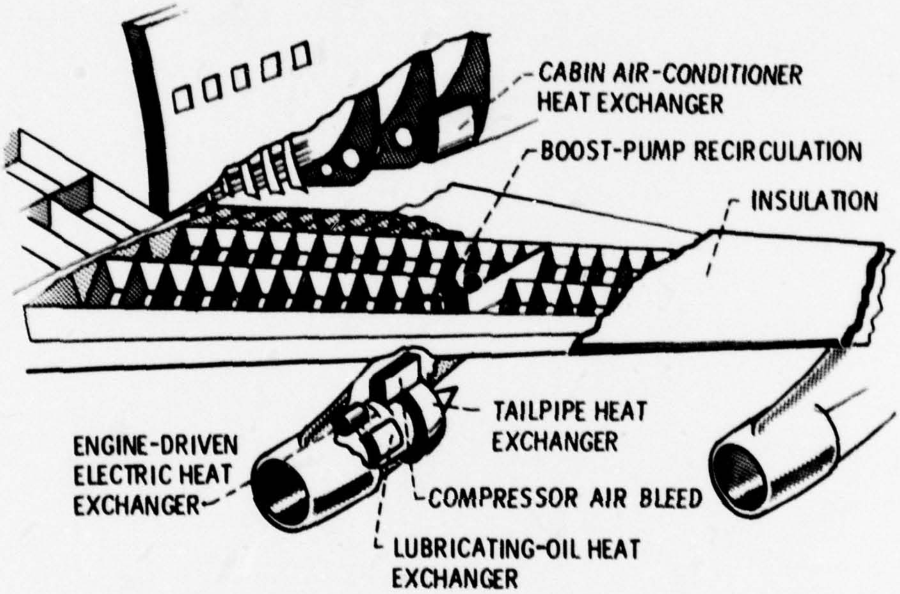

Fig.39 Potential fuel-tank heating sources

ENGINE COMPONENT IMPROVEMENT AND PERFORMANCE RETENTION

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Three general methods of reducing fuel consumption of current engines are listed in Figure 1. Cycle improvement can be incorporated in growth and derivative engine models by changes in bypass ratio, overall pressure ratio and turbine inlet temperature. Component performance can be improved through design refinements. It may be advantageous to incorporate the improved components into existing engines during routine overhaul in addition to incorporation into the future production engines. Improved engine performance retention through revised maintenance procedures and improved design would also reduce fuel usage. This lecture will discuss all three methods of current engine fuel consumption improvement.

The importance of improving the fuel consumption of current engines and their derivative is brought out in Figure 2. Approximately 90 percent of the predicted world commercial aircraft fuel consumption up to the year 2000 will be burned by engines that are in existance today, now under development, or derivatives thereof. Thus, improvement in the fuel consumption of current engine types and their derivatives is mandatory if a significant savings in aircraft fuel consumption is to be made in this century.

An example of cycle improvement in a derivative engine is the refanned JT8D-209. The JT8D-209 (as shown in Figure 3) incorporates the same high pressure spool as the JT8D-9 engine currently in airline service. It has a new low pressure spool with a higher bypass ratio single-stage fan. A picture of the JT9D-209 is shown in Figure 4.

Figure 5 compares the primary cycle variables of the JT8D-209 with the current JT8D-9 and JT8D-17 engines. The JT8D-209 has a higher bypass ratio, a slightly higher overall pressure ratio, and the same turbine inlet temperature as the JT8D-9 engine. A more advanced JT8D derivative engine under study (the STF 517) is also shown. The STF 517 derives its high spool from the JT8D-17 and incorporates a further increase in fan diameter.

The uninstalled altitude cruise SFC's for the JT8D derivatives are compared with the JT8D-9 and JT8D-17 engines in Figure 6. The SFC improvements at maximum cruise thrust due to the cycle changes in the JT8D-209 and STF 517 engines are significant. The actual gains in fuel burned are lower due to the increased weight and drag of the larger fan, and in the case of existing airplanes the engines are operated at a relatively low cruise thrust where the improvement in SFC is less.

The NASA Engine Component Improvement-Performance Improvement program is an integral part of the ongoing JT8D and JT9D engine fuel consumption improvement program. The objectives of this NASA program are shown in Figure 7. The goal of 5% fuel savings over the lifetime of the engine includes the gains due to component performance improvement and improved engine performance retention. Based on studies conducted to date the 5% fuel savings appear technically feasible. However, further performance testing and economic evaluation are required to determine how much of this improvement is economically feasible.

An economic evaluation procedure has been developed as a part of the NASA Performance Improvement Program which I believe is somewhat unique. The general procedure is shown schematically in Figure 8. The engine manufacturer, Pratt & Whitney Aircraft, estimates the impact of each of the component improvements on the engine performance, weight, price, and maintenance cost. The aircraft companies (Boeing and Douglas) translate these into changes in aircraft fuel burned and airplane direct operating cost. The airplane performance and economic data are then fed into TWA's route and economic simulation. This simulation calculates the impact of the component changes on the investment required to incorporate the changes, the direct operating costs, and on fuel burned for TWA'S route system. It also calculates the period of time required for the savings in fuel costs to pay back the initial cost of incorporating each of the improved components in the engines. This calculated payback period is then compared with the maximum acceptable payback period as determined by the participating airlines. If the payback period for a given component improvement is greater than the maximum acceptable value, the improvement is rejected. If the payback period is less than the maximum acceptable time, the cumulative fuel savings for that concept are calculated. The cumulative fuel savings are based on the engine market projection for sales up to 1990 as determined by the team of manufacturers and the airline operators. TWA, American, United, Pan American, and Eastern airlines have been active as consultants in this economic evaluation and are members of the performance improvement evaluation team.

The specific component improvements to be tested as a part of the NASA Performance Improvement program were recommended by P&WA and selected by NASA based on consideration of the cumulative fuel saving, payback period (economic attractiveness), and the experimental program cost. (see Figure 9).

This evaluation procedure is an effective means of determining which of the many potential engine component improvements make economic sense. We plan to use it in the future in Connecticut with our continuing in-house engine improvement program.

Figure 10 shows the number of JT8D and JT9D performance improvement concepts that were screened and processed through the detailed evaluation procedure. Programs were proposed to NASA on three JT8D and five JT9D performance improvement concepts.

The three JT8D performance improvement concepts selected are shown in Figure 11 along with their calculated payback periods, improvement in aircraft direct operating costs, and cumulative fuel savings. The estimated total fuel savings is about 3.5 billion litres (0.9 billion gallons) through the 15 year life of engines entering service through 1990. These performance improvement concepts will be discussed in subsequent charts.

The revised JT8D high pressure turbine outer air seal concept is shown in Figure 12. The current blade discharges all of the cooling air at the blade tip. In the revised scheme most of the cooling air discharge is relocated to the suction side of the blade by plugging and drilling the current blade. This allows the addition of another knife edge seal on the blade tip and the extension of the honeycomb seal material to the trailing edge of the existing spoiler. The objective is a 0.5% reduction in cruise SFC.

The JT8D high pressure turbine root discharge blade (see Figure 13) incorporates a two pass cooling system with improved cooling effectiveness. This reduces the cooling air required and eliminates the momentum loss due to the discharge of cooling air on the suction side of the blade. It is estimated that the root discharge blade will provide a 0.8% reduction in fuel consumption beyond the revised high pressure turbine outer air seal configuration.

The JT8D trenched tip high pressure compressor concept is shown in Figure 14. The use of abradable rub strips through the high pressure compressor permits running with tighter tip clearances. A sprayed Nichrome-polyester abradable appears most promising based on cost, erosion, and abradability considerations. It is estimated that the tighter tip clearance plus a moderate trenching of the outer case will provide a 2% improvement in compressor efficiency. This translates into approximately 0.9% reduction in cruise fuel consumption.

The selected JT9D performance improvement concepts are listed in Figure 15 along with their calculated payback period, direct operating cost improvement, and cumulative fuel savings. The total potential fuel savings is over 9 billion litres (2.4 billion gallons).

The improved JT9D-7 fan concept is shown in Figure 16. The fan performance is improved by the elimination of one of the part span shrouds and by incorporation of improved fan blade aerodynamics (multiple circular arc cross section). Fan blade chords are increased in order to avoid blade flutter and to provide satisfactory foreign object damage characteristics. The heavyweight blade has been tested extensively to provide design information for the lightweight blade. It is estimated that the revised fan will provide a reduction in block fuel consumption of 1 to 1½%.

The JT9D-7 trenched tip high pressure compressor concept is shown in Figure 17. The concept is the same as in the JT8D high pressure compressor but differs in mechanical detail.

Figure 18 shows the improved JT9D-59/70 high pressure turbine active clearance control. The JT9D-59/70 high pressure turbine is encircled by perforated pipes which spray fan air on the turbine case. The air supply is turned off during takeoff, climb, and landing when the engine is subjected to the most severe thermal and structural loads. Since the case is hotter with the air turned off, thermal expansion of the case and seal supports provides larger clearances between the turbine blade tips and the seals. The cooling air is turned on during cruise and the shrinkage of the case and seals tightens the tip clearance, improving turbine efficiency. The improved system incorporates increased coolant air supply and a reduced striking distance for the impingement jets. This will give a greater reduction in outer air seal diameter at cruise and therefore a greater improvement in cruise SFC. The objective is a 0.9% improvement in cruise fuel consumption.

Ceramic coating of the JT9D first-stage nozzle guide vane endwalls (Figure 19) provides a thermal barrier or insulating effect which allows a reduction in cooling air and a consequent performance improvement. Further development may allow thermal barrier application to vanes and blades in the future.

The JT9D-7 graded ceramic high pressure turbine outer air seal concept is shown in Figure 20. The combination of a ceramic outer air seal and an abrasive blade tip provide a considerable improvement in abradability relative to current shroud/blade material combinations. This permits use of tighter tip clearances. Also the ceramic shroud material acts as an insulator thereby reducting cooling air requirements. A potential cruise SFC improvement of 0.4% is estimated for this concept. A picture of a JT9D blade with abrasive blade tip and a cross section of the ceramic seal is shown in Figure 21.

The overall benefits of the JT8D/JT9D ECI Performance Improvement programs are shown in Figure 22. The total estimated fuel saving is nearly 13 billion litres (over 3 billion gallons) and approximately 1.5 billion dollars at an assumed fuel cost of 11.6 cents per litre (40 cents per gallon).

I will now discuss our efforts to understand and improve engine performance retention. Figure 23 shows the general characteristics of SFC deterioration for a specific engine in airline service. There is a rapid initial performance deterioration which is called short time deterioration. Then a more gradual "long term" deterioration occurs, with periodic improvements in performance on engine removal and repair. The amount of performance recovery on repair depends on the extent and nature of the work done. The dotted line shows a typical deterioration for an average repaired engine. The objective of the performance retention technology program is to reduce the SFC deterioration of the average repaired engine by between 1 and 3% over the lifetime of the engine.

The cornerstone of the performance retention technology effort is the NASA JT9D Engine Diagnostics program. The specific objectives of the program are shown in Figure 24. The bottom line is to recommend performance retention techniques for current and future engines through improved maintenance and operating procedures and improved design.

Task I of the engine diagnostics program (Figure 25) was directed at gathering and analyzing historical data on performance deterioration and engine parts usage. Performance data has been gathered from January 1st 1977 backward as far as possible. In addition, gas path parts with various levels of usage (time and cycles) were inspected to define rates of change in dimensions with usage. This was done in order to better understand the losses in module performance and to correlate this with parts life. The Boeing and Douglas aircraft companies and Northwest, Pan American, Trans World, United, and American Airlines participated with us on this part of the program.

Task II (Figure 26) is directed at collecting new data on in-service engine performance deterioration under more controlled conditions. Performance data in-flight, and pre- and post-repair calibrations are being gathered on Pan American 747SP aircraft fleet. Dimensional data and parts replacement/refurbishment data is also being collected for each engine shop visit in order to correlate the performance changes with the mechanical condition of the parts.

Flight load data is also critical to understanding the causes of engine deterioration. The feasibility of obtaining in-flight loads data has been examined, and the possibility of proceeding with the test program to gather certain types of in-flight data is under consideration. The Boeing and Douglas aircraft companies have participated with us in this task.

Task III (Figure 27) is directed at determining the causes of short term performance deterioration. Task III has three fundamental parts: 1) Performance monitoring over the initial life of selected JT9D-7A 747SP engines. Instrumented testing and analytical teardown of one of the short term SP engines. 2) Analysis using finite element methods to determine critical clearance changes under

flight load and transient conditions, and performance calculations to determine the effects of the clearance changes on specific fuel consumption. This analysis covered deterioration during acceptance flight testing, and short term and long term deterioration in airline service and 3) Preparation for testing a JT9D-7A engine on the X-ray test stand under simulated aerodynamic flight load conditions to determine actual clearance changes as compared to those predicted by the structural analysis program. This will provide a more precise calibration of the clearance prediction system. Boeing, Douglas, and Pan American are the participants in Task III.

Task IV (Figure 28) is directed at understanding the causes of long term deterioration. P&WA is conducting extensive back to back testing on specific engines being refurbished in the P&WA Service Center. The results of these tests will broaden understanding of the causes of deterioration and impact of specific module repairs on performance recovery.

Figure 29 shows the areas where a large majority of deterioration losses occur. Each of these areas may contribute to short or long term deterioration. The purpose of the program is to identify the role each area plays and to determine means for reducing the losses in current and future engines in an economical manner.

Fleet average pre-repair TSFC deterioration rates were defined for those operators where pre-repair data was available. (Figure 30). The test data was plotted versus cycles as this was found to be the significant variable (versus hours). A significant spread in the deterioration rate was found between airline operators.

The major reasons for this variation are associated with individual operator maintenance standards relative to the mechanical condition of the gas path parts. The mechanical condition of the cold section of the engine is related to cumulative exposures to flight load and erosion and therefore is cyclic related. The hot section component performance is believed to be repair standard oriented. Cumulative cycles or hours should play a role in hot section performance, however, the data does not correlate with either. It does correlate with airline build standards. The overall individual fleet trend therefore is established by combination of flight length and the efforts that the operator has made historically in maintaining a low level of cumulative damage in gas path parts. Replacement practices, repair standards and in particular the standards utilized in establishing clearances are most important. The data gathered in this program should provide the guidance needed to re-evaluate historical practices and reshape maintenance programs to give lower fuel consumption and lower operating cost.

The distribution of the sources of JT9D engine performance deterioration by component is shown in Figure 31. The increasing contribution of cold section components with increasing cycles can be observed from the historical data.

The preliminary model of the JT9D engine performance deterioration by damage mechanism is shown in Figure 32. The short term rapid increase in specific fuel consumption is due almost wholly to increase in critical seal and blade tip clearances due to flight load effects. Deterioration of fan and compressor performance due to erosion is the major contributor to the long term engine deterioration. The contribution of the turbine to long term deterioration is relatively small because of the requirement for relatively frequent blade and vane placement for durability reasons. Detailed examination of parts with known usages has permitted improved understanding of the role of parts condition in engine component performance deterioration. Analytical estimates of component performance based on these part conditions suggest there are short comings in our understanding that need to be corrected by additional studies and component testing. The component performance losses versus usage models are therefore preliminary until completion of the additional work planned.

Figure 33 shows the effect of erosion on the JT9D high pressure compressor ninth-stage blades. The correlation of erosion with cycles rather than hours can be observed. Significant erosion of the blade tip occurs beyond approximately 2500 to 3000 cycles. No discernible difference was found in the erosion rate in wing mounted engines on the DC-10 and 747 airplanes. Significantly less erosion was evidenced by the tail mounted DC-10 engines.

The variation of erosion with usage in the JT9D 15th-stage high pressure compressor blades is shown in Figure 34. The steel rear stages of the high pressure compressor appear to be less susceptible to erosion than are the titanium mid stages.

As mentioned earlier, the primary cause of short term deterioration is the effect of flight loads on the engine operating clearances. An overview of the analytical model which simulates the performance loss due to flight load effects is presented as a flow chart in Figure 35. The sources and interplay of data which is required to simulate the seal and tip clearance damage and performance deterioration process are illustrated. Boeing and Douglas aircraft defined the flight profile, selected the operating conditions where maximum flight loads occur, and defined the maximum flight loads for their respective aircraft. The effect of asymetric loading on engine deflection was calculated by a NASTRAN structural model which simulates the engine-nacelle-pylon structure. This model was jointly developed by Boeing and P&WA. The effect of axisymmetric loads and engine transients on the baseline clearances were calculated by P&WA analytical procedures. The effect of offset grinds and prior damage were taken into account in determining local interferences. These local interferences plus the abradability factors (the relative wear of blade and knife edge seals versus the abradable material they rub against) then determine the local increases in clearance.

The loss in component performance is calculated from the average clearance increase in that component. The loss in TSFC is then calculated using the performance influence coefficients for each component.

The NASTRAN finite element model used to predict the structural deflections is shown in Figure 36. This analytical model was used to predict the effect of engine build clearances on short and long term deterioration (Figure 37). The deterioration is expressed in percentage loss in TSFC relative to that engine's performance before first flight. The deterioration rate for an engine build with minimum clearances is seen to be significantly higher than one with maximum initial clearances. However, the performance of the engine built on the minimum end of the clearance range is always better than that of one built initially with maximum clearances.

Figure 38 compares the NASTRAN analytical prediction of short term deterioration for minimum and maximum engine build clearance tolerances with measured engine performance test data. Most of the engine test data points fall within the band predicted by the NASTRAN calculations, and the average data show about the same increase in TSFC with flight cycles as the NASTRAN data. The measured deterioration of the PAA short term 747SP engine (P-695743) falls in the middle of the predicted band.

The NASTRAN predicted deterioration due to flight loads is compared with the airline long term fleet average data in Figure 39. As noted earlier the flight load effects are the predominant cause of performance deterioration up through about 2000 flight cycles.

The fan rub patterns calculated by the NASTRAN model are compared with rub patterns measured in the PAA SP engine P-695743 after 141 flights, and in a 747 certification engine in Figure 40. The correlation of predicted and observed data is quite good. In some stages the correlation in rub patterns was not this good. However, the predicted and measured average wear data agrees well in all stages. The good correlation between calculated and observed performance deterioration, average rub wear, and specific rub patterns gives us a pretty fair degree of confidence in our NASTRAN analytical model. However, additional work is required to further perfect the model including X-ray testing of a JT9D engine under simulated flight conditions.

Figure 41 summarizes the conclusions on flight load effects on engine performance deterioration. Flight loads do have a significant effect on performance deterioration. The modeling work carried out on the diagnostics program has improved our understanding of short term deterioration causes. The correlation between the analytical prediction and measured clearance changes are acceptable. However, further refinements are desired to better understand specific rub pattern variation. In-flight load predictions are needed for use in the NASTRAN structural program in order to design future engine installations for minimum engine operating clearances.

Although the work under the engine diagnostics program is far from complete, a number of preliminary maintenance action recommendations have been made. Some of the major recommendations are listed in Figure 42. Fan blade leading edge bluntness increases with time due to the effects or erosion with resultant performance deterioration. It is recommended that the fan leading edge shape be restored after 3000 cycles. Low pressure compressor tip clearances increase with time due to the effects of erosion of the rubber outer air seals. It is recommended that the low pressure compressor rub strips be replaced at somewhere between 2200 and 2500 cycles. The erosion in the high pressure compressor primarily affects blade length and outer air seal material. The high pressure compressor should be completely refurbished between 2500 and 3500 cycles with long blades and new or refurbished rub strips in all stages. It is also recommended that the high pressure compressor stators as well as the blades and outer air seals should be replaced at between 5000 to 7000 cycles. When the burner is repaired the dimensions and particularly the cone angle should be restored and the fuel nozzles removed and cleaned. Turbine durability and performance loss differences between the airlines can be traced to variations in burner repair practices. More precise definition of which dimensions are the most critical must await further testing. Performance deterioration in the high pressure turbine is dominated by tip clearance considerations. It is essential that the tip clearance be set within a tight tolerance band on turbine restoration.

The estimated impact of the suggested performance retention actions on specific fuel consumption are shown in Figure 43. The suggested performance recovery actions, amount of recovery anticipated, and the average specific fuel consumption recovery have been modeled. The results indicated an average TSFC recovery of 2½% at sea level conditions over the 3000 to 6000 cycle interval. This corresponds to a recovery of 2% of fuel consumption at typical cruise conditions.

A preliminary cost benefit study indicates that the suggested maintenance actions will also have a favorable effect on airline economics. The cost of the additional cold section and burner maintenance procedures tend to be offset by the beneficial effect of these changes on turbine maintenance cost. This is a result of lower average turbine inlet temperature levels, lower rotor speeds, and improved turbine inlet temperature profile. The reduction in fuel usage then gives a net reduction in aircraft DOC.

The status of the JT9D Engine Diagnostics program is summarized in Figure 44. Task I efforts have been completed. Tasks II, III, and IV are continuing and will be directed at refining the component models and a better understanding of the effect of flight loads on deterioration.

Figure 45 gives an overview of the conclusions and recommendations of the JT9D engine diagnostic program to date.

- **Cycle improvement**
  - Growth and derivative engines
- **Component performance improvement**
  - Existing engines
  - Future production of current engines
  - Growth and derivative engines
- **Engine performance retention**
  - Improved maintenance procedures
  - Improved design

Figure 1 Current Engine Performance Improvement

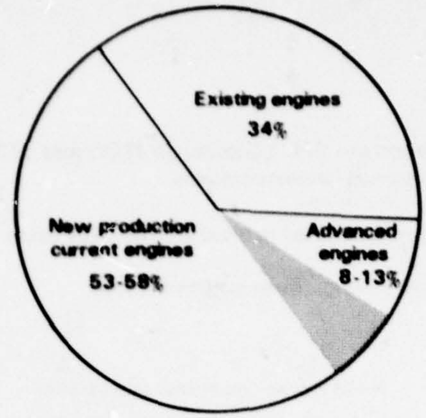

Figure 2 Predicted World Commercial Aircraft Jet Fuel Consumption (1980-2000)

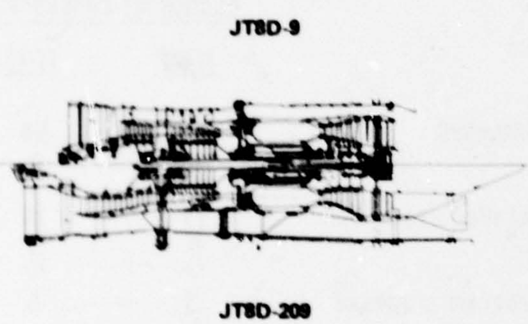

Figure 3 Comparison of the JT8D-9 and Refanned JT8D-209

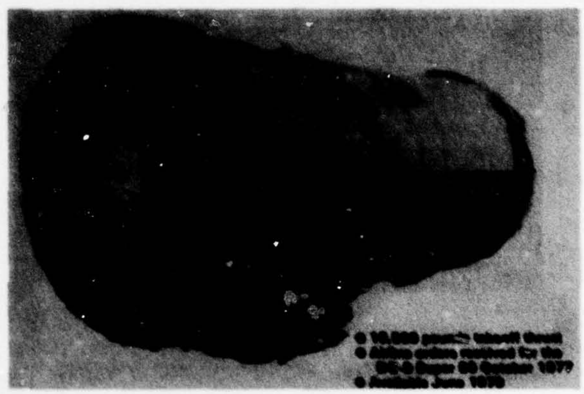

Figure 4 JT8D-209 – A Modern Derivative Engine

	JT8D-9	JT8D-17	JT8D-209	STF-517M*
T. O. Thrust, lb	14,500	16,000	18,500	21,785
Bypass ratio	1.04	1.02	1.65	2.39
Overall pressure ratio	15.9	16.9	18.6	17.9
Turbine inlet temp. (max), °C (°F)	1020(1,865)	1100(2,015)	1010(1855)	1090(1997)
Fan diameter, in	40.5	40.5	49.2	55.2

*Study engine

Figure 5 Cycle Variables of JT8D Engine Family

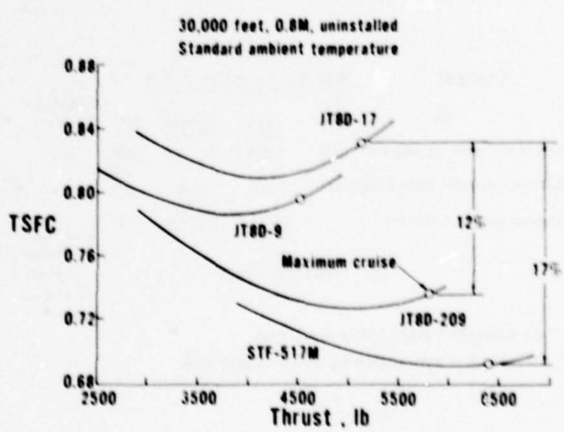

Figure 6 Modern Technology Provides Lower Fuel Consumption

- Demonstrate SFC benefits of JT8D and JT9D component improvements
- High probability of production incorporation
- 5% fuel savings over engine lifetime

Figure 7 NASA Engine Component Improvement – Performance Improvement Program Objectives

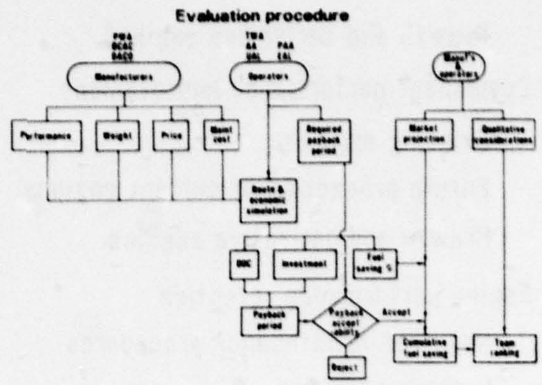

Figure 8 Current Engine – Component Improvement

Considerations:

- Fuel savings
- Payback period
  - New engines
  - Retrofit
- Program cost

Process:

PWA recommendation ⟹ NASA decision ⟹ Demonstration program

Figure 9 NASA – Performance Improvement Program Concept Selection

	Number of concepts:	
	JT8D	JT9D
Screened	41	54
Detailed evaluation	11	18
Program proposed	3	5

Figure 10 ECI – Program Improvement Concept Selection

Concept	Pay back period, Yrs.* New	Retrofit	DOC	Fuel savings** 10^9 liters
Revised HPT outer air seal (-15/-17)	3.9/5.2	5.4/7.0	-0.1	0.3
Root discharge HPT blade (-15/-17)	0/0	0/0	-0.3	1.0
Trenched tip HPC (-15/-17)	1.2/1.4	5.0/6.0	-0.4	2.2
Total fuel savings				3.5 billion liters (0.9 billion gals.)

* For Boeing 727/Douglas DC-9 applications

** 15 year life of engines entering service through 1990

Figure 11 JT8D Performance Improvement Concepts Selected

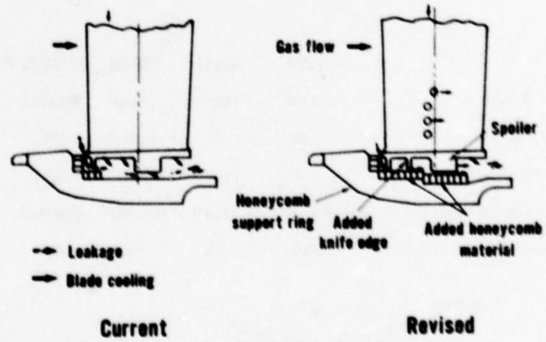

Figure 12 JT8D Revised HPT Cooling and Outer Air Seal

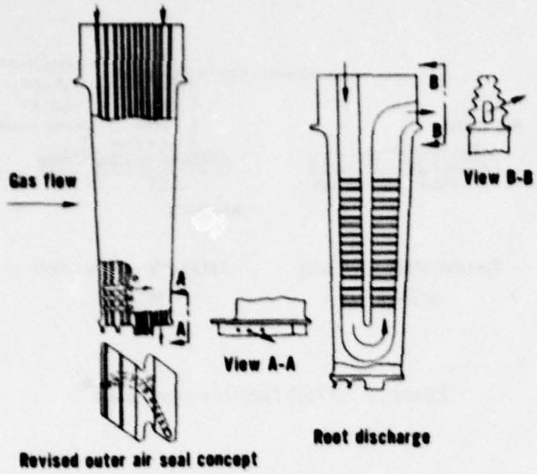

Figure 13 JT8D HPT Root Discharge Blade

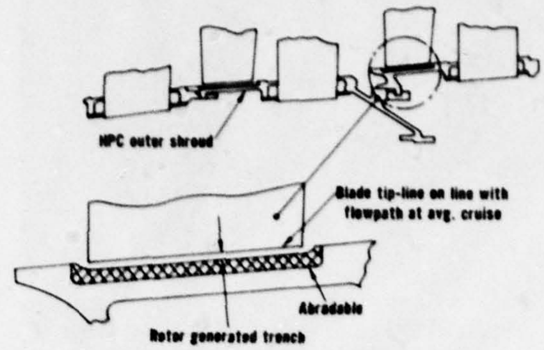

Figure 14 JT8D Trenched Tip HPC

Concept	Pay back period, Yrs* New	Pay back period, Yrs* Retrofit	DOC percent	Fuel saved** 10^9 Liters
JT9D-7 improved fan	0.9/-	10/-	-0.8	2.7
Improved HPT active clearance control (7,70/59)	1.0/2.1	6/12	-0.3	1.8
Trenched tip HPC (7,70/59)	0.1/0.1	0.7/0.3	-0.3/-0.2	1.9
Thermal barrier coating HPT nozzle endwalls	0	0	-0.3	1.0
JT9D-7 ceramic HPT outer air seals (7,70/59)	0.3/0.5	0.5/0.7	-0.3/-	2.0
Total fuel saving				9.4 billion liters (2.4 billion gallons)

* For Boeing 747/Douglas DC-10 applications
** 15 year life of engines entering service through 1990

Figure 15 Concepts Selected JT9D Performance Improvement

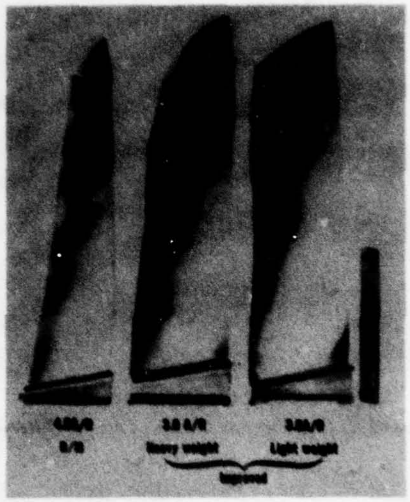

Figure 16 JT9D-7 Improved Fan

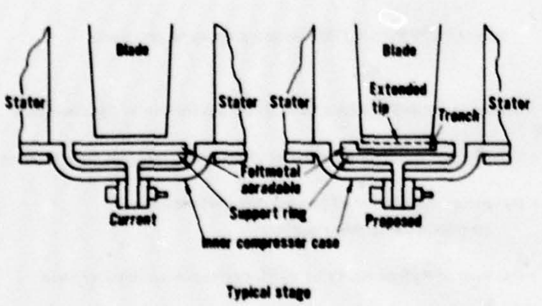

Figure 17 JT9D Trenched Tip High Pressure Compressor

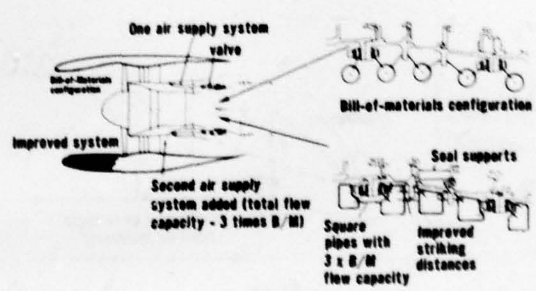

Figure 18 JT9D-70/59 Improved High Pressure Turbine Active Clearance Control

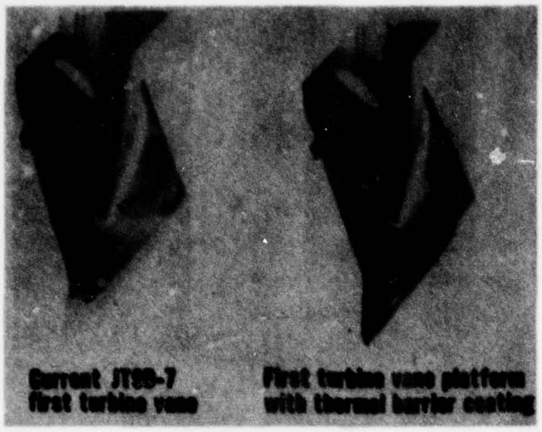

Figure 19 JT9D Thermal Barrier Coating

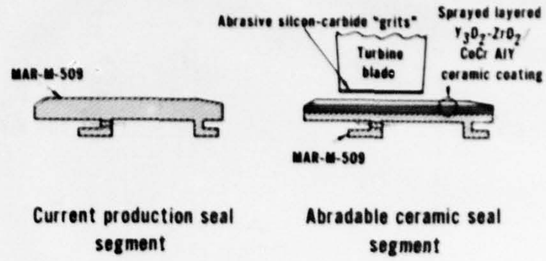

Figure 20 JT9D Turbine Outer Airseal

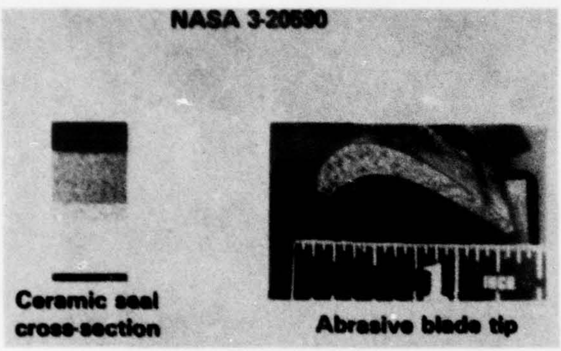

Figure 21 JT9D High Pressure Turbine Ceramic Outer Air Seal

	JT8D	JT9D	Total
Fuel saving - billion liters (gallons)	3.5 (0.9)	9.4 (2.4)	12.9 (3.3)
Fuel cost saving - billion dollars*	0.4	1.1	1.5

*Assumed fuel cost = 11.6¢/liter (40¢/gal.)

Figure 22 JT8D/JT9D ECI–Performance Improvement Program Benefits

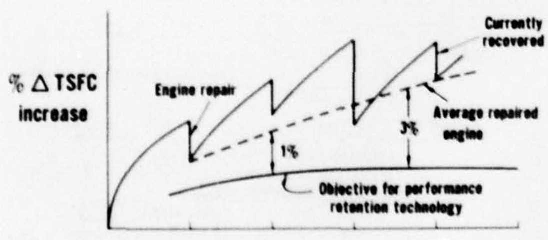

Figure 23 General Characteristic of TSFC Performance Deterioration

Objectives - NASA JT9D engine diagnostic program

- Determine short and long term JT9D performance deterioration
- Identify and quantify sources of short and long term deterioration
- Determine sensitivity of component performance to engine parts deterioration
- Develop analytical model of JT9D performance deterioration
- Recommend performance retention techniques for current and future engines

Figure 24 Current Engines Reduced Deterioration

Collection and analysis of:

- **Historical performance data**
- **Historical parts usage and repair rate**

Participants

- **BCAC, DAC, PAA, NW, TWA, UAL, AL**

Figure 25 Task I – Performance Deterioration – Existing Data

- **Flight data gathering**
- **Ground facility data gathering**
- **Flight load instrumentation feasibility study**
- **Participants -BCAC,PAA,DACO**

Figure 26 Task II – In-Service Engine Performance Deterioration

Low time engine test and analytical refurbishment

- Performance monitoring
- Test planning
- Engine preparation, test, refurbishment

Analytical program

- Structural deflection analysis - finite element
- Performance deterioration calculations

Engine x-ray test plan

- Test planning
- Loading device conceptual design

Participants

- BCAC, DAC, PAA

Figure 27 Task III – Short Term Performance Deterioration

- **Internally funded P&WA programs**
- **On-going service center refurbishment**
- **Special back-to-back test results**

Figure 28 Task IV – Long Term Deterioration

Seals

- Clearance control/rub out/erosion
- Sharpness of knife edges
- Flatness of lands

Blades and vanes

- Airfoil length
- Airfoil shape - bluntness/roughness
- Blends

Cases

- Flange leakage
- Out of roundness/flatness
- Leakage due to looseness

Figure 29 Areas Where Losses Occur

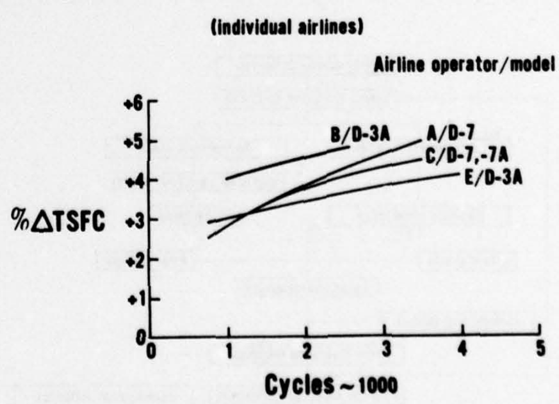

Figure 30 JT9D Pre-Repair Test Data Relative To New At Constant Thrust

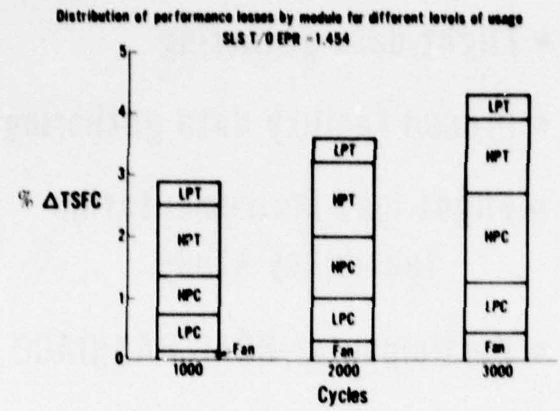

Figure 31 Sources of Performance Deterioration

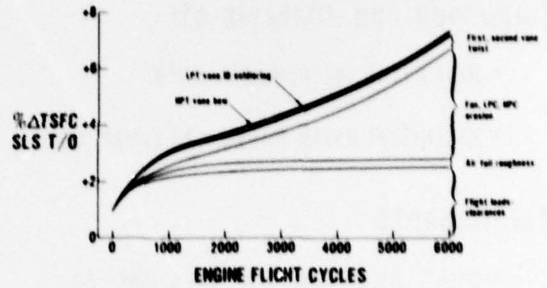

Figure 32 Preliminary Model of JT9D Engine Performance Deterioration By Damage Mechanism

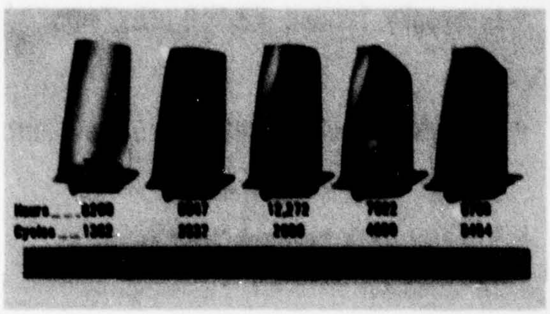

Figure 33 JT9D High Pressure Compressor 9th-Stage Blades

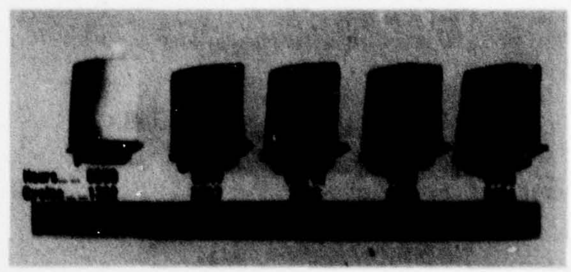

Figure 34 JT9D High Pressure Compressor 15th-Stage Blades

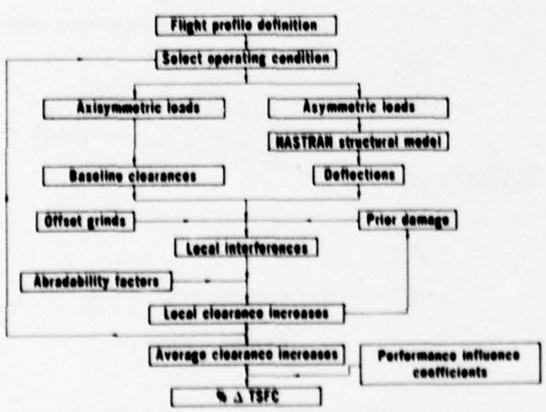

Figure 35 Analytical Model Flow Chart

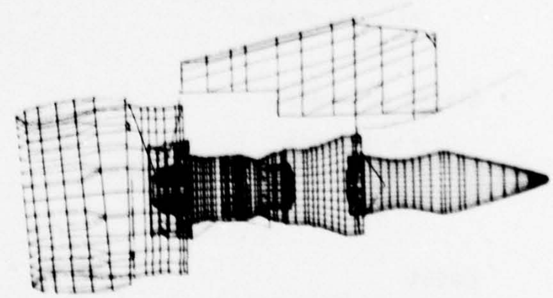

Figure 36 JT9D-7/747 Integrated Nastran Structural Model

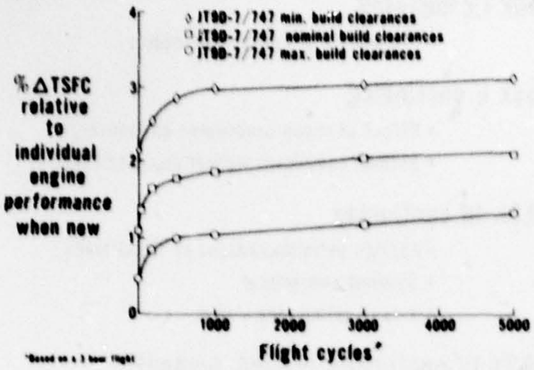

Figure 37 Predicted Effect of Build Clearance On Short Term and Long Term Deterioration

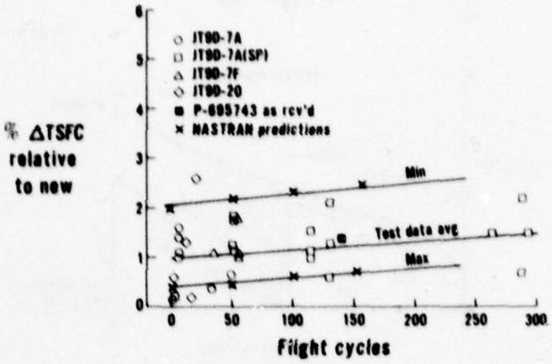

Figure 38 Short Term Deterioration

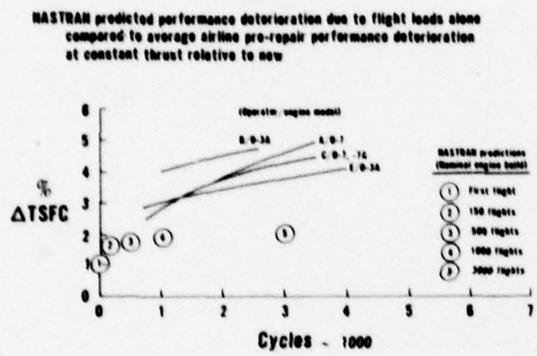

Figure 39 Pre-Repair Test Data Relative To New

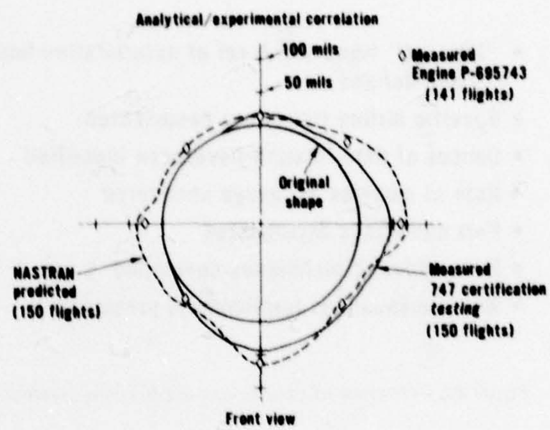

Figure 40 Fan Rub Patterns

- **Flight loads have significant effect on performance deterioration**
- **Modeling improved understanding of short term deterioration causes**
- **Correlation between analytical prediction and measured clearance changes acceptable–further refinements desired to understand specific rub pattern variations**
- **In-flight load predictions needed for future engine clearance optimization**

Figure 41 Conclusions

- **Restore fan leading edge - 3000 cycles**
- **Replace LPC rubstrips - 2200-3500 cycles**
- **Completely refurbish HPC - 2500-3500 cycles**
- **Revane HPC - 5000-7000 cycles**
- **Restore burner dimensions, cone angles, clean fuel nozzles - each access**
- **Restore blade tip clearances to nominal in h.p. turbine**

Figure 42 Major Preliminary JT9D Maintenance Recommendations

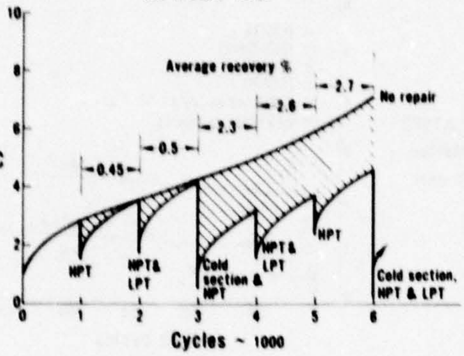

Figure 43 *Impact of Suggested Performance Retention Actions on TSFC*

Task I completed
- Preliminary definition and models

Task II continuing
- Effect of repair procedures on recovery
- Refined component models and cost benefits

TASK III continuing
- Refined definition-impact of flight loads
- Dynamics-analytical
- X-ray testing plan - III B

TASK IV continuing (P&WA funded)
- Effect of module replacements/repairs
- Refined component models

Figure 44 *Program Status*

- "Average" trend and level of deterioration has been defined
- Specific airline trends are documented
- Causes of deterioration have been identified
- Role of modules vs. usage uncovered
- Part conditions documented
- New modeling techniques developed
- Recommendations (preliminary) presented

Figure 45 *Overview of Conclusions and Recommendations*

LOW ENERGY CONSUMPTION ENGINES

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A general outline of the material to be covered in this lecture is given in Figure 1.

Before discussing low energy consumption engines of the future, I would like to briefly review the historical development of improved economy in aircraft gas turbine engines. Figure 2 shows the historical progress in aircraft gas turbine cruise efficiency. The data extends from the first English (Whittle W1) and German (Von Ohain He5-36) turbojet flight engines up to today's modern high bypass ratio commercial turbofan engines. Also shown are the cruise efficiencies of the Napier Nomad turbocompound engine and the commercial turboprop engines in the 50's. The compound engine and some of the turboprop engines had significantly higher cruise efficiencies than the contemporary jets or fans due to the higher propulsion efficiency of the propeller. However, they were restricted to lower cruise Mach numbers due to the limitations of the propeller.

The aircraft gas turbine cruise efficiency has improved by a factor of 3 over the four decades of engine development. Significant improvement is predicted for the future by further refinement of the cycle and propulsion characteristics. The increases in overall cycle pressure ratio, turbine inlet temperature, and compressor and turbine polytropic efficiencies that have accompanied this engine efficiency improvement are plotted in Figures 3 through 6. Rapid progress was made in advancing all of these cycle parameters over the first decade and a half. Since then, rapid progress in overall pressure ratio and turbine inlet temperature has continued while further development in compressor and turbine efficiencies has been slow and difficult to achieve. Continued increases in compression ratios are projected for the future with only modest increases in turbine inlet temperature and component efficiencies.

It should be pointed out that it is an achievement even to maintain constant component efficiencies while increasing compression ratio and turbine inlet temperatures. Good component efficiency is more difficult to achieve at higher pressure ratios due to the smaller sized blading in the high pressure compressor and turbine components and increased leakage losses. Higher turbine inlet temperatures tend to degrade turbine efficiency due to increased cooling air requirements and leakage.

Future gas turbine efficiency improvement can follow two paths that are not mutually exclusive (Figure 7). The first path is the evolution of the turbofan cycle to give improved performance by means of further cycle and component improvements. The second approach would develop an alternative cycle in addition to continued component refinement.

First, I will discuss the possibilities for further evolution of the turbofan powerplant and some of the work that is going on today to bring about these improvements.

The focus of our long term turbofan technology improvement is the NASA Energy Efficient Engine (E^3) Program. Figure 8 shows the objectives of the NASA E^3 Program. These objectives are the development, by 1985, of the technology to permit at least a 12% reduction in specific fuel consumption relative to today's high bypass ratio turbofan engine as typified by the JT9D-7A, and to achieve at least a 5% reduction in airplane direct operating costs (DOC) relative to a comparable airplane powered by JT9D-7A engines. The E^3 must, at a minimum, be designed to meet the latest FAR 36 noise requirements and the anticipated emissions regulations. An added objective is a 50% reduction in performance deterioration relative to the JT9D-7A.

Two evaluation aircraft were used as a guide in making design decisions in the E^3 program. (See Figure 9). The aircraft requirements were arrived at on the basis of input from Boeing, Douglas and Lockheed Aircraft Companies. The first is a transcontinental domestic trijet carrying 440 passengers with a design range of 5500 kilometers. An average stage length of 1300 kilometers was used for calculating fuel burned and direct operating costs. The second is an international quadjet carrying 510 passengers with a design range of 10,200 kilometers and the fuel burned and direct operating costs calculated for an average stage length of 3700 kilometers.

The calculated effect of turbine inlet temperature and overall pressure ratio on the fuel burned by the international quadjet is shown in Figure 10. Takeoff turbine temperature is shown on the vertical scale and overall pressure ratio on the horizontal scale with contours of constant fuel burned. A fan pressure ratio of 1.74 was assumed and bypass ratio adjusted at each point to give minimum fuel consumption. This approach gives near optimum fuel consumption at each of the combinations of turbine inlet temperature and overall pressure ratio. Component efficiencies were assumed consistent with a 1985 design time. With these assumptions, minimum fuel burned occurred at a pressure ratio approaching 50 and takeoff turbine inlet temperature of approximately 1430°C (2610°F). This powerplant cycle would provide about a 5% reduction in fuel burned relative to a JT9D cycle engine incorporating the same advanced technology. It should be noted that there is only a small gain to be made in fuel burned by raising the turbine inlet temperature above the current JT9D levels.

The variation in bypass ratio that goes along with the different values of turbine inlet temperature and overall pressure ratio is shown in Figure 11. Bypass ratio is seen to increase rapidly with increasing turbine temperature and to decrease slowly with increasing overall pressure ratio.

Thus, one would choose a high overall pressure ratio for the E^3 in order to minimize the amount of fuel burned. However, increasing the overall pressure ratio and increasing the turbine inlet temperature both tend to increase initial engine cost and engine maintenance cost, everything else being equal. These effects tend to counterbalance the economic advantages of the lower fuel burned. An economic study was conducted to evaluate the effects of the design variables on aircraft direct operating cost (DOC). The results of the economic evaluation for international quadjet are shown in Figure 12 where contours of constant aircraft direct operating costs are plotted as a function of the primary cycle variables. These results are based on the use of 11.9 cents per litre fuel and 1977 economic assumptions. The size of the aircraft and its powerplants were adjusted to give the same payload and range for each combination of pressure ratio and turbine temperature and priced accordingly. The replacement life of the hot section gas path parts was assumed constant (as metal temperature was held constant by varying the amount of cooling air). The price of the hot section parts was increased with increasing pressure ratio and turbine temperature to account for the increased complexity of the cooled parts. Under

these assumptions the optimum direct operating costs occur at a compression ratio slightly above 40 and at the JT9D-7 level of turbine inlet temperature. However, the primary cycle variables can be varied over a fairly wide range without significantly affecting the direct operating costs.

It is likely that in the future, fuel costs will increase more rapidly than the other aircraft direct operating costs. This would make higher engine pressure ratios even more attractive economically. There is no economic incentive to increase turbine inlet temperature above today's operating levels.

As a result of these and more detailed studies, the E^3 design parameters were selected as shown in Figure 13. The corresponding JT9D-7A engine values are given for comparison. An overall pressure ratio of 38 and a combustor exit temperature of 1425°C (2600°F) were chosen as giving the best balance between potential fuel consumption improvement and program risk. A bypass ratio of 6.5 was selected on the basis of achieving the best combination of installed weight and performance. The fan pressure ratio was set slightly above 1.7 in order to achieve best performance and to set the primary jet velocity at a level such that noise levels 4 dB below FAR 36-7 could be achieved. A fan tip speed of 455 meters per second (1500 fps) was selected in order to achieve acceptable fan stability margin at the desired fan pressure ratio level. The E^3 engine incorporates an exhaust stream mixer in order to further improve fuel consumption and reduce jet noise levels.

The exhaust stream mixer transfers energy from the turbine exhaust gas to the fan exit air by mixing. If done efficiently, this can provide a 3 to 5% improvement in specific fuel consumption at maximum cruise conditions relative to a non-mixed engine of the same diameter.

Figure 14 shows a picture of an exhaust mixer that is being developed as a part of the JT8D-209 engine. This is a convolted mixer of advanced design and high efficiency. Pratt & Whitney Aircraft has also tested a number of small-scale models of convoluted mixers for high bypass ratio engines. Some of the model test results are shown in Figure 15. Mixer efficiency is plotted as a function of the mixer length to diameter ratio. The E^3 mixer efficiency goal is higher than those demonstrated by the model tests. Further mixer design analysis and model testing is planned. Hopefully the 85% goal of the E^3 program can be met.

Figure 16 shows the estimated effect of the exhaust mixer on the E^3 engine characteristics and aircraft performance. A potential reduction of over 4% in fuel burned and approximately 2% reduction in aircraft DOC relative to a non-mixed engine is shown. These preliminary studies do not include such effects as wing interference drag and possible pylon and wing weight penalties. Further effort in design, mixer model testing, and nacelle/wing wind tunnel model testing is required to determine whether the estimated mixer benefits can be made a reality. The potential of the mixer is sufficient to warrant such an evaluation program.

The use of gearing between the low pressure compressor and fan was seriously considered in the E^3 study. The use of the gear permits lower fan tip speeds and higher bypass ratios (both of which favor lower fuel consumption and lower noise) without compromising the design of the low pressure compressor and low pressure turbine. A cross section of the geared engine is shown in Figure 17. The geared engine is more complex in that it incorporates the added gearbox component and an air-oil cooler to reject the gear generated heat. Some sort of safety provision would be required in order to prevent turbine rotor run-away in the event of a serious gearbox failure.

Figure 18 shows the effect of bypass ratio on the cruise fuel consumption of the direct drive and geared fan engines. Figure 19 shows the corresponding variation in fuel burned for the intercontinental aircraft operating at its average stage length; and Figure 20 the aircraft direct operating costs. A bypass ratio of 6½ was selected for the direct drive engine and a bypass ratio of 9 for the geared engine based on obtaining near minimum operating costs and fuel burned. These evaluation studies show the geared fan engine to have approximately 1% lower fuel burned than the direct drive engine and about 1% higher aircraft direct operating cost. A comparison of some of the key design parameters of the geared and non-geared engines is shown in Figure 21.

The direct drive engine was selected for E^3 as the 1% fuel burned advantage of the geared fan engine was not judged sufficient to offset its increased cost and added complexity and risk.

A preliminary layout of the E^3 engine is shown in Figure 22. It is a two-spool engine configuration. The high spool incorporates a 14:1 pressure ratio 10 stage compressor driven by a single-stage high pressure turbine. The burner is a two-stage Vorbix combustor design evolving from the NASA Clean Combustor Program. The high pressure rotor is straddle mounted between two bearings. The low rotor consists of a single-stage shroudless hollow titanium fan and a four-stage low pressure compressor driven by a four-stage low pressure turbine.

The engine incorporates just two main support sections located directly before and after the high pressure rotor. The fan ducts are structurally integrated with the engine in order to minimize engine deflection and clearance changes under flight load conditions. The engine also incorporates an exhaust stream mixer just upstream of the propulsion nozzle. Duct noise attenuation treatment is integrated with the duct structure.

Planned advanced design features for the E^3 are listed in Figure 23. The design features are listed in three categories: those that primarily improve TSFC, those that improve weight and cost, and the one which improves emissions. Some of these technologies will be discussed in more detail.

The principle of the supercritical airfoil providing shock free flow at high subsonic Mach numbers is shown on the right hand side of Figure 24. A conventional airfoil with flow acceleration to supersonic speeds and a consequent shock wave is shown on the left. Limited cascade testing of the supercritical airfoils has shown an increase in blade critical Mach number relative to conventional double circular arc airfoils and low losses over a wider range of incidence angles at all approach Mach numbers (see Figure 25). This gives promise of improved efficiency at both design and off design condition.

Recent studies of engine deterioration conducted under the NASA Engine Component Improvement Engine Diagnostics Program have indicated that the major causes of engine performance deterioration are the rubbing out of the blade tip and seal clearances, and erosion of the fan and compressor airfoils. The E^3 design incorporates a number of features to help minimize deterioration due to these causes. (See Figure 26). Among these features are the structurally integrated fan ducts which minimize engine deflection under flight loads; and the use of active clearance control to open up the compressor and turbine blade tip clearances under flight conditions

where engine transients and flight loads would be anticipated to cause blade tip and seal wear. Lower aspect ratio blading along with erosion resistant coatings will be used in the compressor to minimize the effect of erosion.

The single crystal material used in the E^3 turbine airfoils is an evolution from our earlier work on directionally solidified turbine arifoils. Figure 27 shows JT9D blade castings of conventionally cast material; directionally solidified material with columnar grains aligned with the primary stress axis of the blade; and single crystal blades formed from a single grain with no grain boundaries in the blade. Directionally solidified turbine blades are now incorporated in several JT9D production models. Single crystal turbine blades have undergone successful engine testing and are continuing in development.

The patented process of casting both the directionally solidified and the single crystal blades is illustrated in Figure 28. The process begins with the pouring of molten metal into the mold. In the case of the directionally solidified blades, water chills the base plate and the grains are formed along the vertical axis as the blade is slowly withdrawn from the furnace. In the case of the single crystal blades, the same process is used. However, the helical selector permits only a single grain to pass up into the blade, and as the blade is withdrawn from the furnace it is formed by a single grain of the material. Current directionally solidified blade production facilities can readily be used to cast single crystal blades.

The absence of grain boundaries means the single crystal alloy does not require the constituents normally required to strengthen the grain boundaries - Carbon, Boron, Hafnium, and Zirconium. The result is that improved alloys can be developed having increased strength and temperature capabilities. Figure 29 shows that the current single crystal material has a 28°C (50°F) higher creep capability than the directionally solidified material at the same stress level. Advanced alloys under development will provide an additional 28°C (50°F) increase in metal temperature capability.

Figure 30 shows that the relative low cycle fatigue life of the single crystal material is also clearly superior. For a given applied stress, the LCF life of the single crystal material is eight times that of the conventionally cast material and twice that of the directionally solidified material.

An improved high temperature disk material, MERL 76, is under development and will be available for the E^3 program. Figure 31 compares the properties of MERL 76 with two of the alloys now in commercial service. The improvement in bore strength, stress rupture temperature capability at rim stresses, and relative LCF life provided by MERL 76 are quite significant.

Figure 32 shows the relationship between efficiency and rim speed for high pressure turbine stages. A single-stage high pressure turbine driving a 14:1 high pressure compressor requires a very high rim speed (approximately 520 m/sec) in order to achieve a reasonable efficiency level. This is about 20% higher than the turbine rim speed required for a comparable engine designed using a two-stage high pressure turbine. The highly loaded single-stage has inherently lower efficiency than the two-stage design as a result of the high Mach numbers required in the nozzle guide vanes and blading.

A comparison of the E^3 and JT9D-7 high pressure turbines is given in Figure 33. The E^3 turbine delivers more work per kilogram of gas in one stage than the JT9D turbine does in two. An increase in rim speed of 50% is required to accomplish this. Since stresses tend to increase with the square of the rim speed, considerable refinement in the design of the blade, its attachment, and the disk, as well as materials improvement, will be required in order to achieve satisfactory commercial life. For instance, it is necessary to taper blade thickness from root to tip in order to reduce blade root and attachment stresses. Our objective is to reduce the turbine cooling and leakage air by a factor of almost 2 through the use of a single-stage turbine incorporating improved single crystal alloy airfoils.

The biggest potential payoff of the single-stage turbine is the large reduction in the number of high pressure turbine airfoils, about 80 percent, that appears achievable by use of advanced materials. Since high pressure turbine airfoils account for approximately one third of today's high bypass ratio turbofan engine maintenance material costs, this airfoil reduction could substantially reduce costs if the airfoil parts lives and costs can be maintained at today's levels.

As shown by Figure 34, MERL 76 advanced disk material is required in order to achieve disk life and burst margin design requirements. Use of a current material in the high pressure disk would require a significant increase in the number of rotor blades in order to achieve an acceptable burst margin. This increase in blade count eliminates the potential operating cost advantage of a single-stage high pressure turbine.

The estimated completion dates for the major tasks of the NASA E^3 program are shown in Figure 35. This program will provide the substantiation of the technologies required to design a commercial turbofan in the mid 80's having the capability of 12 to 15% reduction in specific fuel consumption compared to today's high bypass ratio turbofans.

Next, I will discuss the potential alternative cycles. Figure 36 lists the alternative cycles evaluated under the NASA study of "Unconventional Aircraft Engines Designed for Low Energy Consumption". Alternative primary cycles and propulsors were evaluated. The check marks indicate the more attractive cycles which will be discussed further.

A comparison of the thermal efficiency of the most attractive primary cycles is shown in Figure 37. The regenerative and compound engine cycles with projected future technology could potentially provide thermal efficiencies comparable to the simple gas turbine cycle. However, they are heavier, more bulky, and considerably more complex. Thus, primary cycles other than the high pressure ratio do not appear attractive at this time for large commercial aircraft powerplants.

Propulsive efficiency is a key parameter in discussing propulsors. The effect of propulsor diameter on the ideal propulsive efficiency at Mach 0.8 is shown in Figure 38. Conventional turbofans and conventional propellers are shown on the two extremes of the curve. There is an intermediate diameter on the order of twice the diameter of a conventional turbofan that appears of interest in that it approaches the ideal propulsive efficiency of a conventional propeller and is about half its size. There are two propulsor candidates that fall into this diameter range; the shrouded propeller and an advanced propeller concept called a prop-fan.

The propulsive efficiencies of a conventional turbofan, a shrouded propeller of 1.1 fan pressure ratio, and an advanced propeller (prop-fan) with a 1.05 pressure ratio are shown in Figure 39. The ideal propulsive efficiency is shown for each of these propulsors and

their corresponding installation losses. Both the shrouded propeller and the prop-fan offer the potential of significantly higher propulsive efficiency than a conventional turbofan. However, a more detailed investigation of the shrouded propeller uncovered serious stability and weight problems. Therefore, the prop-fan was selected for further investigation.

A picture of a prop-fan model is shown in Figure 40. The prop-fan uses 8 to 10 relatively low aspect ratio blades. The blades are swept back near the tip for improved cruise performance and reduced noise. The blades are of spar and shell construction, similar in major aspects to current proven production designs. The blades consist of a flattened metal tube spar, a composite airfoil shell, and a titanium leading edge sheath for foreign object damage and erosion protection. This configuration has been analytically shown to meet the aerodynamic and structure requirements. Uncontained blade fragmentation is not considered to be a major problem, based on 60 million hours of propeller operation without a single incident. The nacelle is contoured to decelerate the flow entering the root section of the blades. This flow deceleration is required in order to avoid exceeding the critical Mach number of the blading near the root. The prop-fan disk loading is approximately 4 times that of a conventional propeller.

Some of the prop-fan design parameters are compared with the Electra propeller in Figure 41. Thinner blade sections are used to achieve the high blade critical Mach numbers required for efficient 0.8 Mach number cruise.

Three prop-fan models of 62.23 cm (24.5 in) in diameter were fabricated and wind tunnel tested to determine their performance. Figure 42 shows a picture of a blade from each of the models. The work was done by Hamilton Standard under contract from NASA-Lewis. The latest model, SR-3, incorporates increased sweep-back in the tip region in order to improve cruise efficiency and to reduce the near field noise level at cruise and climb conditions.

Results from the prop-fan model tests are compared with the goal efficiencies in Figure 43. The SR-3 model gave the best efficiency at Mach 0.8, and was within 1% of the goal. These results give a high degree of confidence that the 80% goal can be exceeded with further refinement. This represents a significant advance in flight Mach number capability relative to the 1950 propellers.

The prop-fan powered aircraft must have cabin comfort levels (noise and vibration) that are comparable to turbofan powered aircraft in order to gain airline and passenger acceptance. Achievement of this goal will be difficult as the fuselage is in the direct noise field of the prop-fan, whereas inlet and exhaust ducting shield the fuselage from turbofan fan noise.

There are several features of the prop-fan which will tend to improve cabin noise relative to conventional propellers. The smaller diameter of the prop-fan permits location further from the fuselage; and its thinner swept-back tips will reduce the level of noise generated. However, extensive fuselage noise attenuation treatment will probably also be required in order to achieve cabin noise levels comparable to turbofan powered aircraft.

Some preliminary prop-fan noise testing and fuselage noise treatment studies have been conducted under NASA sponsorship. Additional prop-fan testing and fuselage attenuation treatment development are needed before a rigorous assessment can be made of the weight penalties associated with achieving a competitive cabin noise level.

Preliminary studies of a medium range aircraft have been made by Boeing, Douglas, and Lockheed to determine the potential fuel burned and direct operating costs benefits of an advanced prop-fan propulsion system. The results of these studies, shown in Figure 44 indicate a potential fuel savings of 10 to 20% and a direct operating cost reduction of 6 to 8%, relative to a comparable aircraft powered with advanced turbofan powerplants. The range of values is due to uncertainties in the drag due to prop wake effects on the nacelle and wing, in the weight of noise treatment required to achieve satisfactory cabin noise levels, and in the maintenance costs of the prop-fan and reduction gear.

The NASA prop-fan program is currently in the Phase I technology effort (Figure 45). This phase covers tests of prop-fan models to determine their noise and performance characteristics, tunnel tests of prop-fan/nacelle/wing models to determine the drag interaction effects and aerodynamic excitation forces on the propeller blades, studies and tests of cabin noise attenuation concepts, and aircraft evaluation studies to provide program guidance.

Phase II is planned to start in 1980 and will cover testing of a 2.5 m to 3.5 m diameter prop-fan. Ground testing would concentrate on the structural characteristics of the prop-fan, its drive gear and pitch change mechanism. Flight or wind tunnel tests would be conducted to verify the performance and to determine the near and far field noise characteristics. There would be a continuing effort in installation aerodynamics and fuselage acoustic treatment. Phase III would fund testing of a prop-fan powered demonstrator aircraft. This would probably be a modification of an existing aircraft to incorporate the prop-fan powerplants and the fuselage noise attenuation treatment. Such a flight demonstration of the prop-fan is required in order to satisfactorily demonstrate the aircraft's system perform- and operation, and most important to show that cabin comfort levels comparable to turbofan aircraft can be achieved.

In summary, (Figure 46), the E^3 turbofan represents an evolutionary approach with a potential reduction in specific fuel consumption of 12 to 15% relative to today's high bypass ratio turbofan engines. The NASA E^3 Program is underway, and its technology should be substantiated by the mid 1980's. The advanced prop-fan represents a significant change from today's large commercial aircraft powerplants. However, it offers a potential of 25 to 30% reduction in fuel burned relative to today's high bypass ratio turbofans. There are some technical, cost, and customer acceptance uncertainties in connection with the prop-fan that need to be resolved. The NASA prop-fan technology program is underway and a large scale demonstrator program is planned in order to resolve these uncertainties. Prop-fan technology is scheduled to be substantiated in the mid to late 1980's. Other alternative cycles are not currently attractive.

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12. G. E. Holbrook and G. Rosen, "Evaluation of the Turboprop for High Speed Air Transportation", April 1978, ASME Paper No. 78-GT-201.

- **Historical review**
  - **Fuel consumption improvements**
  - **Component improvements**
- **Potential future improvements - Turbofan**
  - **Cycle selection**
  - **Component improvements**
  - **Programs in progress**
- **Alternative cycles**
  - **Review of alternative cycles**
  - **Prop-fan potential and programs**
- **Summary**

Figure 1 Low Energy Consumption Engines

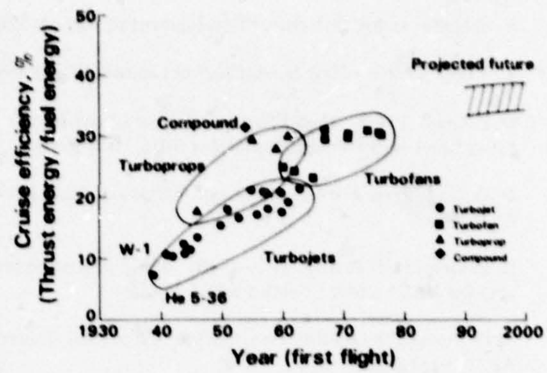

Figure 2 Progress In Aircraft Gas Turbine Efficiency

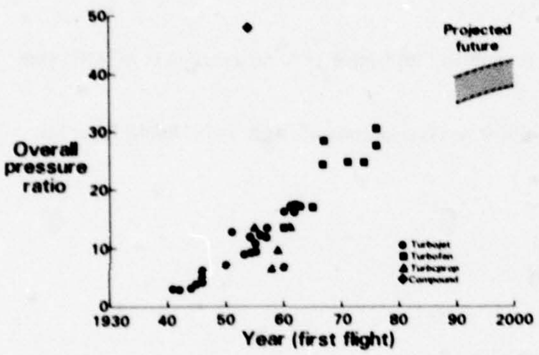

Figure 3 Progress In Aircraft Gas Turbine Compression Ratio

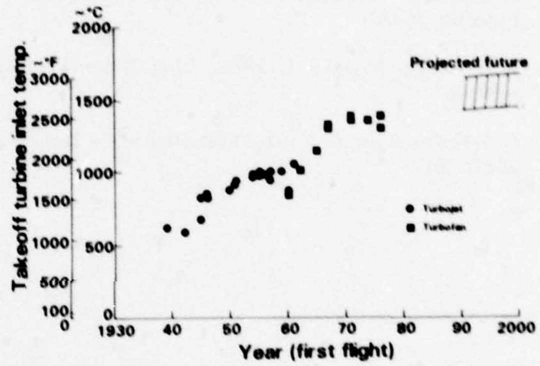

Figure 4 Progress In Aircraft Gas Turbine Inlet Temperature

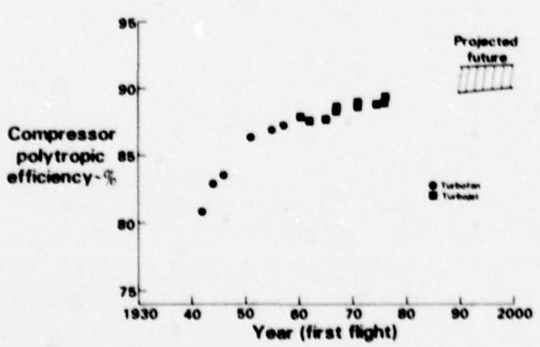

Figure 5 Progress In Aircraft Gas Turbine Compressor Efficiency

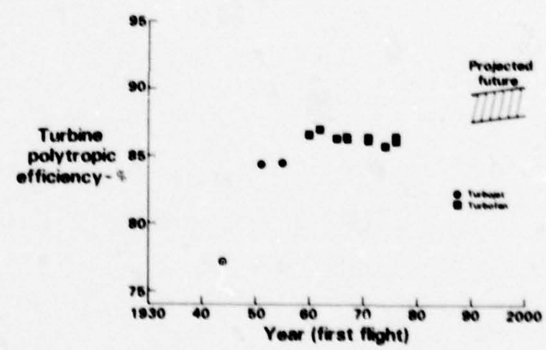

Figure 6 Progress In Aircraft Gas Turbine Efficiency

- **Evolution -**

Turbofan improvement

and/or

- **Revolution -**

Alternative cycle

Figure 7 *Future Development for Lower Fuel Consumption*

Development of technology by 1985 to permit:

- At least 12% reduction in TSFC relative to JT9D-7A
- At least 5% improvement in DOC relative to JT9D-7A
- FAR-36 as amended March 1977
- Meet anticipated emissions requirements
- 50% reduction in performance deterioration relative to JT9D-7A

Figure 8 *NASA Energy Efficient Engine (E^3) Program Objectives*

Domestic trijet

440 passengers
5600 KM (3000 NM) design range
1300 KM (700 NM) average stage length

International quadjet

510 passengers
10,200 KM (5500 NM) design range
3700 KM (2000 NM) average stage length

Figure 9 *E^3 Study Evaluation Aircraft*

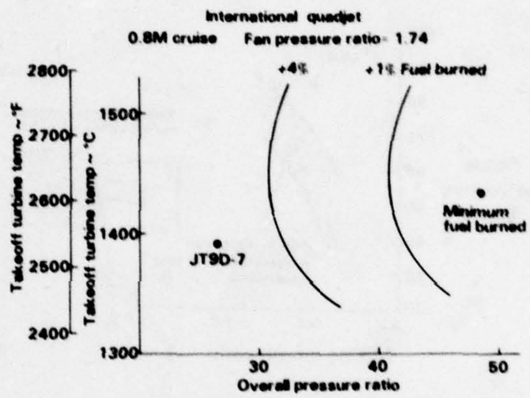

Figure 10 *E^3 Study Effect of Cycle On Fuel Burned*

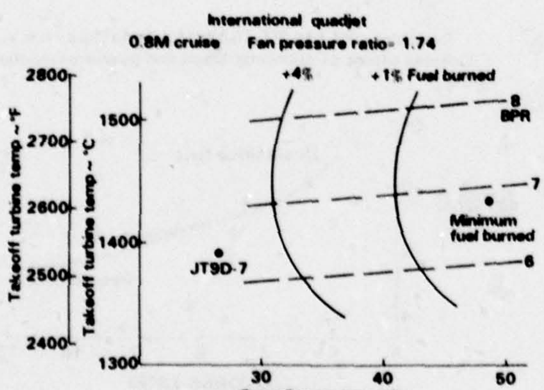

Figure 11 *E^3 Study Effect of Cycle On Fuel Burned*

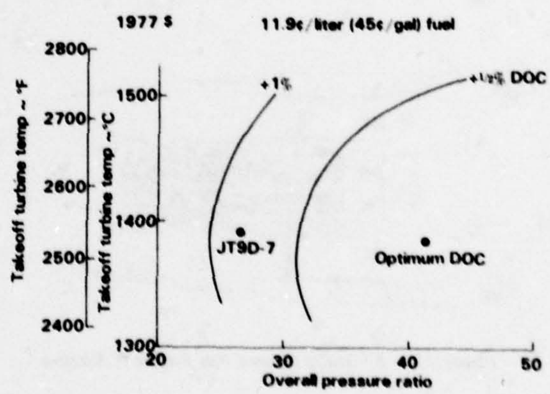

Figure 12 *E^3 Study – Effect of Cycle On Direct Operating Cost*

	JT9D-7A	E^3
Bypass ratio	5.1	6.5
Fan pressure ratio	1.6	1.7+
Fan tip speed ~ m/sec (ft/sec)	410 (1350)	455(1500)
Overall pressure ratio	25	38
Max. combustor exit temp ~ °C(°F)	1370 (2500)	1425 (2600)
Exhaust system	Separate	Mixed

Figure 13 NASA Energy Efficient Engine (E^3) Preliminary Design Parameters

Figure 14 JT8D 209 Exhaust Mixer

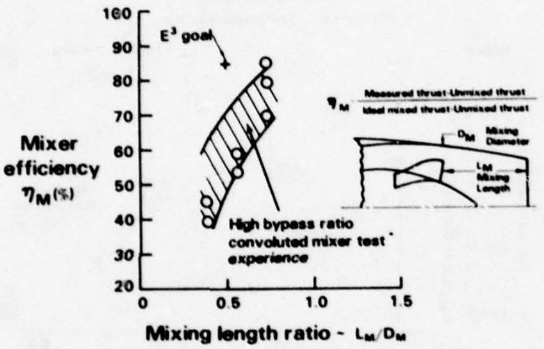

Figure 15 Exhaust Mixer Performance

	Percent change relative to separate flow engine
Installed engine weight	+0.5
Engine length	+12.0
Installed cruise* SFC	-3.5
Fuel burned - Domestic/International	-4.2/-4.6
DOC - Domestic/International	-1.6/-2.3

** 10670M, 0.8 Mn, no wing interference drag*

Figure 16 E^3 Study Estimated Effect of Mixer

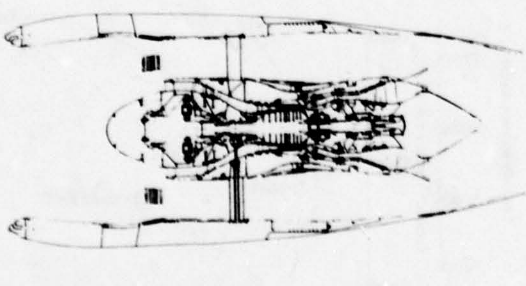

Figure 17 E^3 Study Geared Fan Engine X-Section

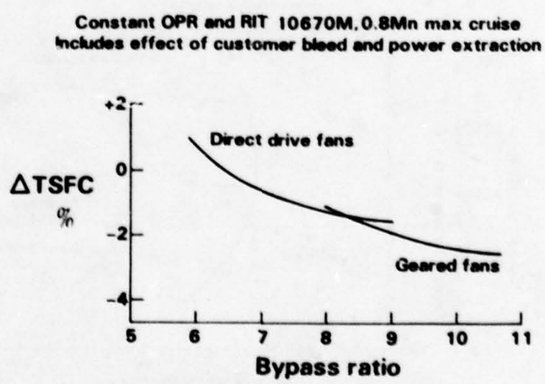

Figure 18 E^3 Study Isolated Nacelle TSFC Trends

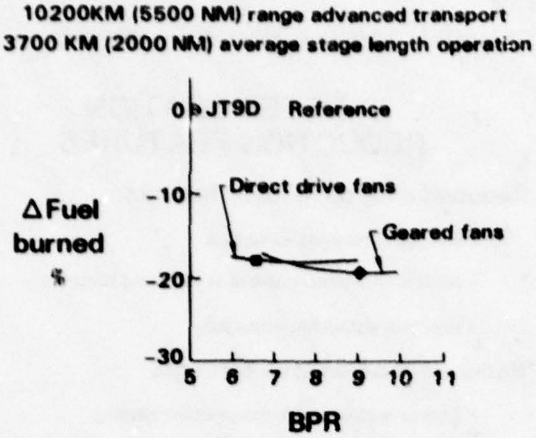

Figure 19 E^3 Study Effect of Bypass Ratio On Fuel Burned

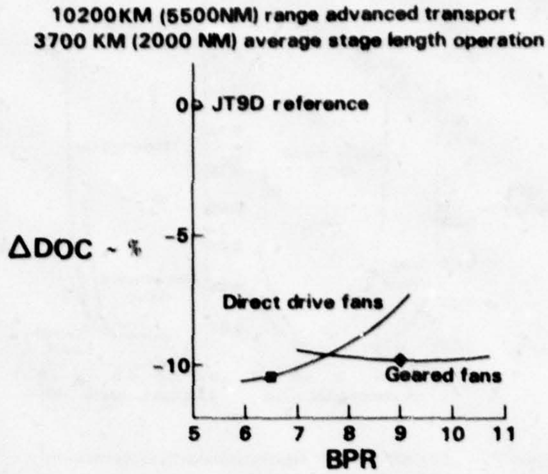

Figure 20 E^3 Study Effect of Bypass Ratio On DOC

Non-geared - 6.5 BPR
Geared - 9.0 BPR

	Percent change non-geared to geared engine
Δ Installed engine weight, %	+12.3
Δ Fan tip diameter, %	+12.6
Δ Fan tip speed, %	- 24
Δ Installed cruise* SFC, %	- 1.9

*10670M, 0.8Mn. max. cruise

Figure 21 E^3 Study Comparison of Geared and Non-Geared Engines

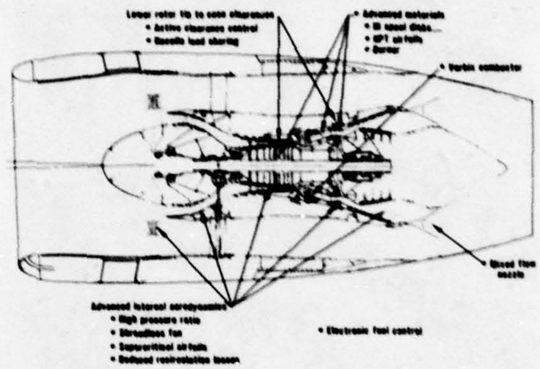

Figure 22 Advanced Turbofan Engine Concept

Performance improvements:
- Shroudless hollow titanium fan blade
- Supercritical compressor airfoils
- Single crystal turbine airfoils
- Graded ceramic turbine outer air seals
- Reduced clearances
  - structurally integrated fan ducts
  - designed for active clearance control
- Short efficient mixer

Weight/cost reductions:
- Increased rotor speeds
- Single-stage high pressure turbine
- Improved compressor and turbine disk materials
- Composite nacelle

Emissions improvement:
- Vorbix combustor

Figure 23 Advanced Turbofan (E^3) Selected Design Features

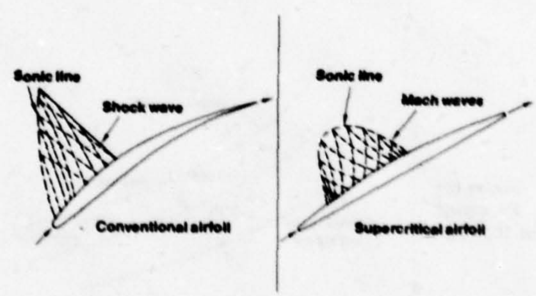

Figure 24 Comparison of Shock-Free Supercritical and Conventional Airfoils At High Mach Number

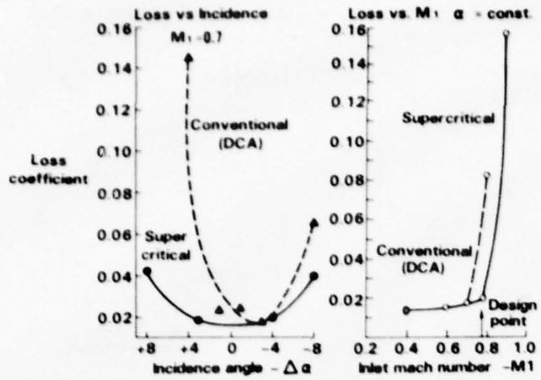

Figure 25 Cascade Results Supercritical and Conventional (DCA) Blading

Objective: 50% reduction from JT9D-7

E^3 DETERIORATION REDUCTION FEATURES

Reduced clearance loss through:

- Integrated nacelle structure
- Active clearance control in HPC and turbines
- Improve abradable materials

Reduced erosion loss through:

- Lower aspect ratio compressor blading
- Thicker blade leading edges
- Erosion resistant coatings

Figure 26 E^3 Performance Deterioration

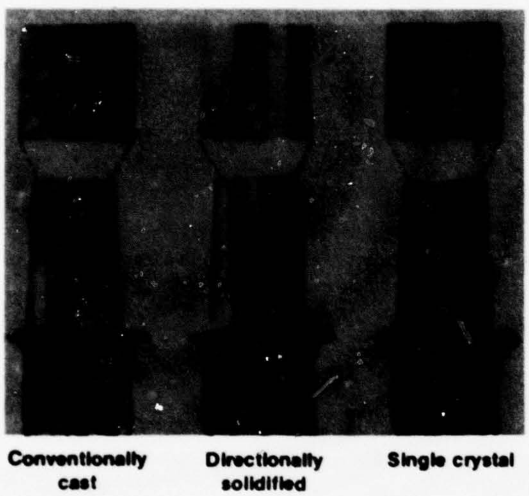

Figure 27 Cast Turbine Blade Material Trends

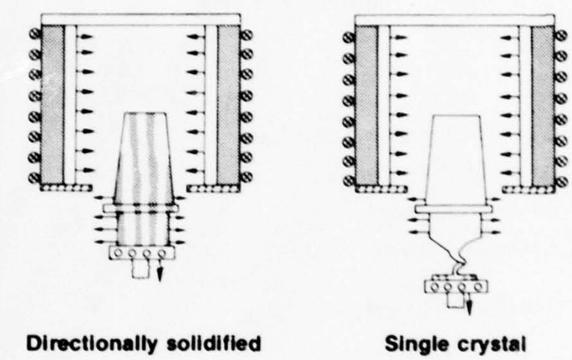

Figure 28 Casting Process

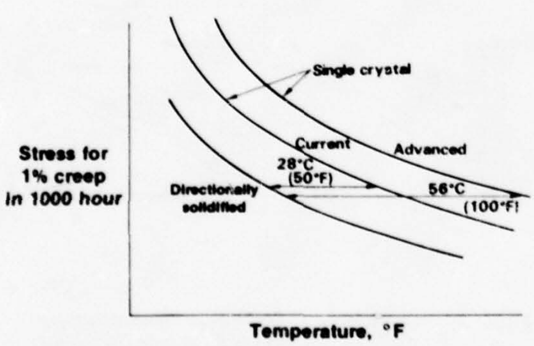

Figure 29 Single Crystal Has Superior Creep Strength

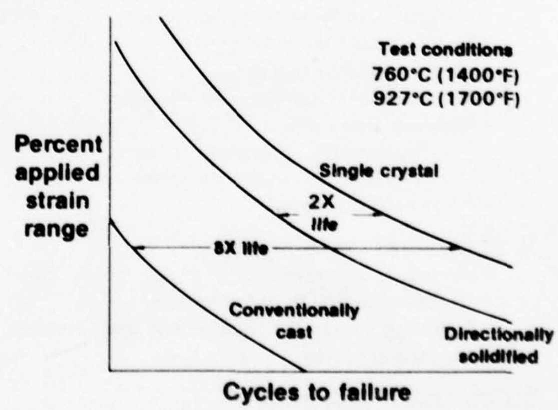

Figure 30 Single Crystal Has Best Low Cycle Fatigue Life

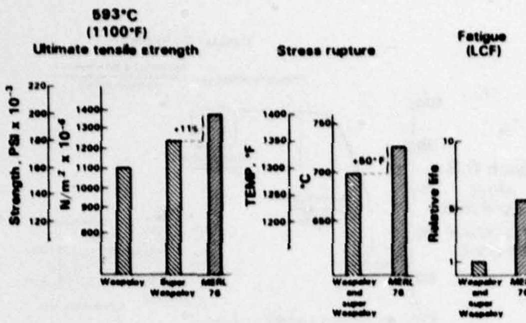

Figure 31 MERL 76: Property Comparisons

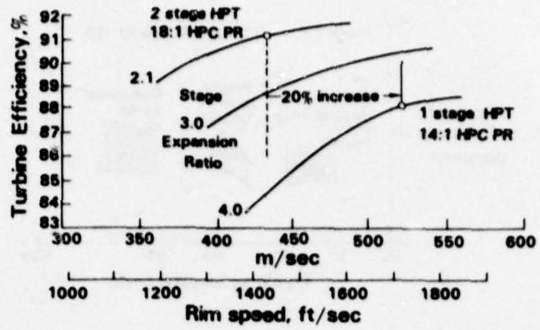

Figure 32 Turbine Rim Speed Requirements

	JT9D-7	E^3
No. of HPT stages	2	1
Pressure ratio	3.87	4.03
Relative work per unit mass	Base	+10%
Relative rim speed	Base	+50%
Relative HPT cooling & leakage air	Base	-46%
Relative number of airfoils	Base	-80%

Figure 33 E^3 High Pressure Turbine Characteristics

	Percent of design requirements		
	Super waspaloy	Astroloy	MERL 76 advanced disk material
Disk rim life (Cylic)	42	42	100
Disk bore life (Cyclic)	42	67	100
Burst margin	27	27	100

Figure 34 E^3 Study Calculated Disk LCF Life Single-Stage Turbine

Task	Completion date
Component design and test	
High pressure compressor	11/80 & 2/82
Combustor	5/82
High pressure turbine	3/82
High spool test	9/82
Testbed engine test	9/83

Figure 35 NASA E^3 Program

Primary Cycles	Propulsor
✓ Simple cycle (Brayton)	✓ Fan
Intercooled	Variable pitch fan
✓ Regenerative	✓ Shrouded propeller
Reheat	✓ Prop-fan
✓ Compound	
Variable compression ratio	

* NASA "Study of Unconventional Aircraft Engines Designed for Low Energy Consumption" NAS3-19465

Figure 36 NASA Study Program Alternate Cycles Evaluated

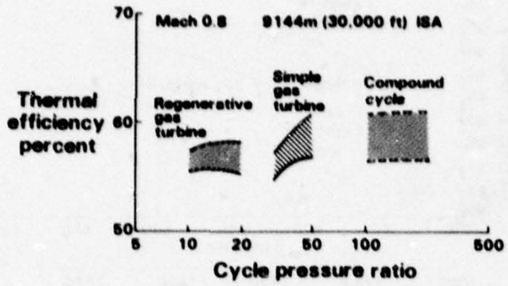

Figure 37 *Comparison of Primary Cycles 1990's Operational Technology*

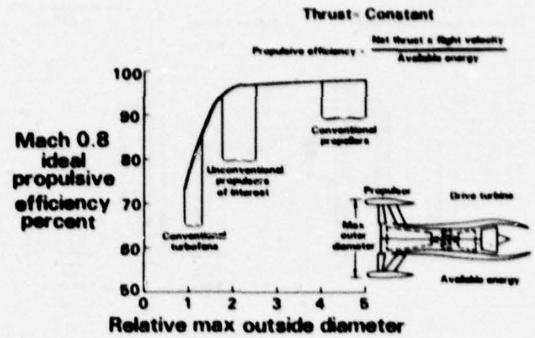

Figure 38 *Effect of Diameter On Ideal Propulsive Efficiency*

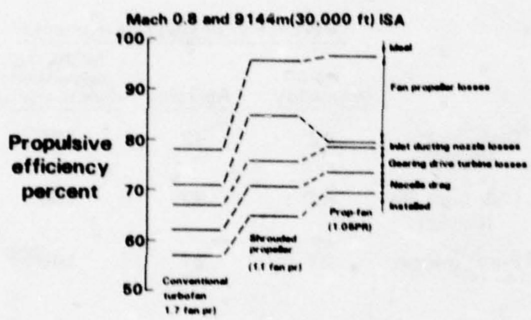

Figure 39 *Comparison of Installed Propulsive Efficiency*

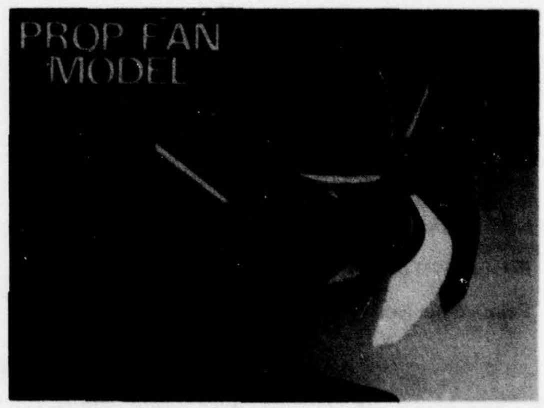

Figure 40 *Prop-Fan Design Characteristics*

	Electra propellor	Prop-fan
Number blades	4	8
Relative diameter	1.9	1.0
Tip speed m/sec (ft/sec)	220(721)	245(803)
Blade t/c		
At radius ratio = 1.0	.03	.02
At radius ratio = 0.25	.20	.12
Disk loading ~ Kwatts/m² (SHP/ft²)	80 (10)	300 (37.5)

Figure 41 *Prop-Fan Characteristics*

Figure 42 *Prop-Fan Models*

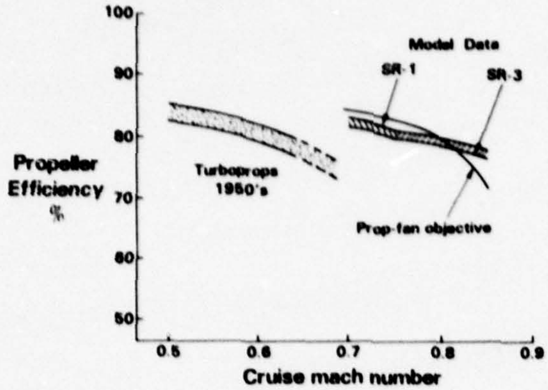

Figure 43 Progress In Propeller Efficiency

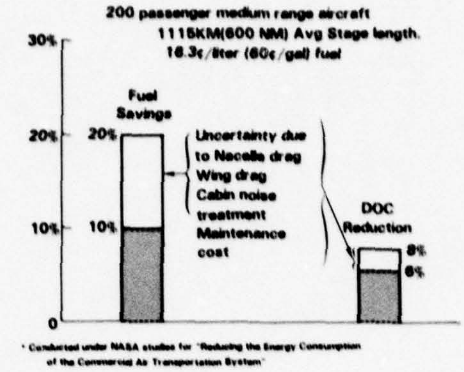

Figure 44 Prop-Fan Potential Benefits Boeing, Douglas, and Lockheed Evaluations

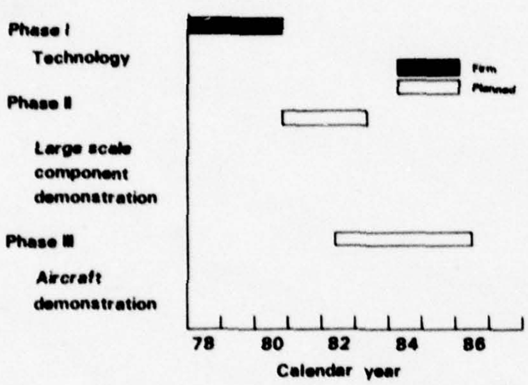

Figure 45 NASA Prop-Fan Program

Advanced turbofan

- Evolutionary
- Potential TSFC improvements 12 – 15%
- NASA E³ demonstrator program underway
- Technology availability ≈ Mid 80's

Advanced prop-fan

- Significant change
- Potential TSFC improvements 25 – 30%
- Some technical/cost/acceptance questions
- NASA technology program underway
- NASA demonstrator program planned
- Technology availability - mid to late 80's

Other alternative cycles

- Are not currently attractive

* Relative to comparable JT9D-7A powered aircraft

Figure 46 Low Energy Consumption Engines Summary

ENERGY CONSERVATION AIRCRAFT DESIGN AND OPERATIONAL PROCEDURES

by Philippe POISSON-QUINTON

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92320 Châtillon (France)

SUMMARY

The main objective of this lecture is to review the most recent studies and applications leading to a better fuel efficiency for the next twenty years air transportation system.

First, the major technological progress in aerodynamics, structures/materials, propulsion integration and in avionics are quantified for the subsonic transport aircraft, but also for future VTOL, STOL and SST.

In a second part, it appears clearly that major improvements on flight and ground operational procedures are in progress ; these improvements must strongly reduce the energy waste of the current civil and military air transportation systems.

LES ÉCONOMIES D'ÉNERGIE LIÉES A LA CONCEPTION DES AVIONS ET AUX PROCÉDURES OPÉRATIONNELLES

Résumé

L'objectif de cet exposé est de passer en revue les plus récentes études et applications destinées à réduire la consommation d'énergie du transport aérien au cours des vingt prochaines années.

En première partie on passe en revue les récents progrès technologiques en aérodynamique, en structures/matériaux, en propulsion intégrée et en avionique, qui vont contribuer à une notable réduction de la consommation de carburant et à une meilleure économie du transport subsonique, mais aussi des avions à essor vertical, à décollage court et à croisière supersonique.

Dans la deuxième partie, il apparait clairement qu'une amélioration importante des procédures opérationnelles en vol et au sol est en cours de développement, ce qui devrait entraîner progressivement une sensible réduction du gaspillage d'énergie actuellement constaté dans les systèmes de transport aérien civil ou militaire.

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FOREWORD and CONCLUSIONS ON ENERGY SAVINGS IN AERONAUTICS

Before explaining how to save fuel in Air Transportation, it is necessary to provide an overview of current and future trends of energy consumption and especially in transportation.

A recent FAA paper [70] has given the U.S. pretroleum consumption by major sectors for the fiscal year 1977 : the total U.S. fuel consumption reaches 18 million barrels per day i.e. 276.10^9 gallons per year (850.10^6 metric tons/ year).

The following table shows that transportation demand is the most important consumer with about 152.10^9 gallons per year (470.10^6 tons):

- Transportation	54.8 %
- Household and Commercial	17.7 %
- Industry	17.1 %
- Electricity Generation, Utilities	10.1 %
- Other	0.3 %

When the petroleum consumption by mode of transportation is considered, the part of Civil Aviation is quite small as shown on the following table :

- Automobiles	53.1 %
- Commercial Buses and Trucks	25.1 %
- Civil Aviation	8. %
- Water	4.6 %
- Trains	2.9 %
- Transit	0.3 %

The 8 percent Civil Aviation share of the transportation consumption corresponds to 4.4 % of the total U.S. fuel usage and represents $12.2\ .10^9$ gallons ($37.7.10^6$ tons) per year.

More precisely the total U.S. Civil Aviation fuel consumption is shared between *international and domestic markets*. The total domestic Civil Aviation (90 % Air Carrier and 10 % general aviation) consumes $9.2.10^9$ gallons per year.

For fiscal year 1977, the air carriers fuel consumption has reached $8.2.10^9$ gallons ($25.4.10^6$ tons) ; only 1 % fuel savings obtained with improved operating techniques would yield total savings of 82.10^6 gallons per year for the U.S. airlines (or $ 30 million a year with a fuel price of 37 cents a gallon).

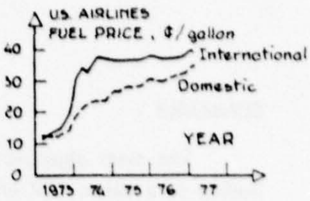
This study reflects the Aviation Energy situation but only the civil aspect ; the U.S. military fuel concumption must be taken into account : from a U.S. Air Force study [8], for fiscal year 1975, military aircraft operations estimated consumption represents 2,2 % of the total U.S. fuel demand ; so the U.S. military aircraft fuel consumption is now less than the civil one ; that is why all the technological and operational improvements must be applied to both civil and military A/C.

In Europe, oil consumption sharing is quite different, with about half the U.S percentage for aviation ; for instance, in 1976 for France, the figures by consuming sectors are as follows [58] :

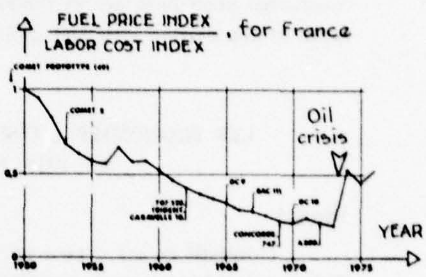
- Transportation	25.7 %
- Residential/Commercial	30.8 %
- Industry, Electricity, etc ...	30. %
- Others	13.5 %

Within the French transportation sector, fuel for airplanes represents about 2 % and about 0.01 % for helicopters ; for the same year 1976, the total fuel consumption for aeronautics in Europe was about 14.5 million tons, i.e. 2.7 % *of the total European fuel consumption.*

Considering the fuel price the following graph shows its sudden increase after the 1973 oil crisis for the U.S. airlines ; the international air carriers were more severely concerned (300 % increase) :



On the other hand, if the evolution of the labor cost index since 25 years is taken into account, the ratio "fuel price index/labour cost index" for 1975 was about the same than at the beginning of the 60's, at least in the French case [51] as shown below :



Nevertheless, the fuel cost will remain a significant part of the flight operating cost ; the far-term fuel price evolution will depend on the *future political and socio-economical conditions* in each country ; these same conditions will govern the expected aviation growth through the end of the 20th century. Both NASA [89] and FAA [90] have recently given an interesting outlook for U.S. aeronautics up to the year 2000, as a function of various scenarios : from limited to expansive U.S. economy growth :

Scenarios (1975-2000)	Fuel consumption	Fuel price
Limited growth	+ 65 %	- 9 %
Expansive growth	+ 342 %	- 36 %

From all these findings, we can draw some general conclusions, valid for all developed countries :

* Fuel usage for aeronautics is a very small percentage of the total oil consumed ; thus, it seems wise to keep the necessary amount of fuel for Aviation, because it is the most efficient and economical source of energy (even in far-term, liquid hydrogen or nuclear energy use is highly unlikely for most A/C missions, both civil and military).

* But, such oil energy will remain expensive for the operators and a penalty for the foreign balance trade of most countries ; that is why a continuous effort will be needed to increase flight efficiency on every type of aircraft : mainly subsonic transport, but also VTOL, STOL and SST.

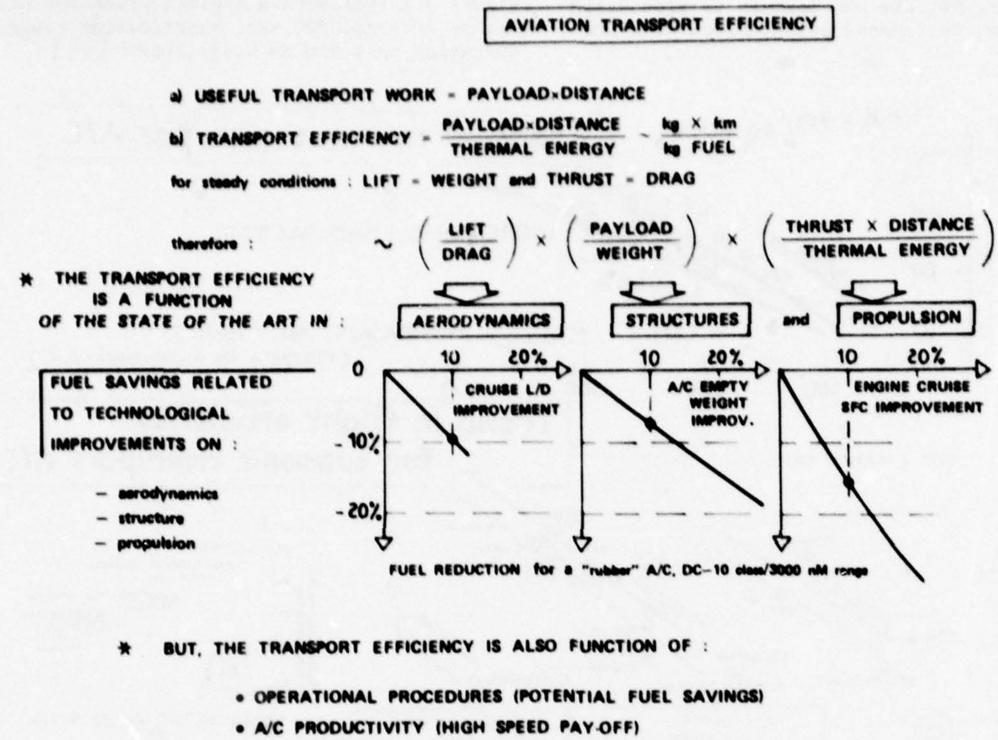


Fig. 1

*Nevertheless, the price to develop new technologies, and to manufacture new types of airplanes and engines is now so high that it is important to analyse their "cost effectiveness", as seen by the user (Airlines are reluctant to pay for reengined old jet-transports, even if the fuel efficiency is 30 % better with new fan-engines, because the price to pay is often not cost-effective for transport A/C operators).

Since the fuel crisis, extensive research and development programs have been oriented towards energy savings, and a large part of the present analysis is directly taken from the recent results published in the last five years in various countries.

- the largest effort is made in U.S where NASA [1,89], the Federal Aviation Administration, FAA [2,90] and U.S manufacturers or agencies [3, 4, 5, 6, 7, 8] have worked together on long term programs oriented on fuel savings.

In Europe, the same objectives are in progress in England [9, 10, 11], in Germany [12, 13], in France [14, 15, 16], etc...

Before analysing the various ways to improve the A/C energy efficiency - except on the engine side, which is the main part of this lecture series - it is interesting to explain what are the various disciplines involved in this technological effort ; the basic formula of the transport efficiency is given on figure 1 to show that progress will be at first a function of improvements in aerodynamics, structures/materials and propulsion, but also in "systems" (i.e. avionics, etc... not shown here) ; but we shall see that the transport efficiency depends strongly upon the operational Flight and Ground procedures, and of course upon the transport productivity, i.e. the mission speed [11].

Figure 2 presents the general trend of flight efficiency over the last 25 years [37, 16], to point out that the flight efficiency index (given here in seat capacity x distance flown divided by the fuel burnt) have grown rapidly for each successive flight regimes (figure 2-c) : low subsonic regime with propellers and high subsonic speed with the turbo-fans ; for the supersonic transport, Concorde is a good technical start of a new era, that opens the way to more efficient derivatives and new SST generations.

The tremendous increase of the subsonic jet efficiency is mainly explained by the introduction of high by-pass turbo-fans with much lower fuel consumption than the first turbo-jets (figure 2-a), but also by the introduction of wide-body-high passenger capacity-Aircraft family (B-747, DC-10/L-1011, Airbus) ; nevertheless, figure 2-b illustrates the very important load-factor problem : increasing load-factors have more pay-off for an Airline than the best technological improvements...(the current mean load-factor for U.S Air carriers was about 53 % for the last years).
Adjusting A/C capacity and frequency to various traffic levels is the key to Airlines economy.

On the manufacturer side, the main problem is to estimate the potential benefits of applying advanced technology and their effects on Aircraft Direct Operating Cost (DOC) which is a criterion of cost-effectiveness ; various, and quite different methods are used for DOC calculation ; in Europe, the EURAC method was developed under A/C manufacturers cooperation ; this method seems well adapted to new improvements ; the most important parameter is the A/C maximum

gross-weight, but the DOC formula is also based on A/C price, fuel consumption, block-time and thrust.

Figure 3 illustrates a typical breakdown of DOC for an advanced 200 seat short/medium range A/C operating on a 500 nM stage length [12]:

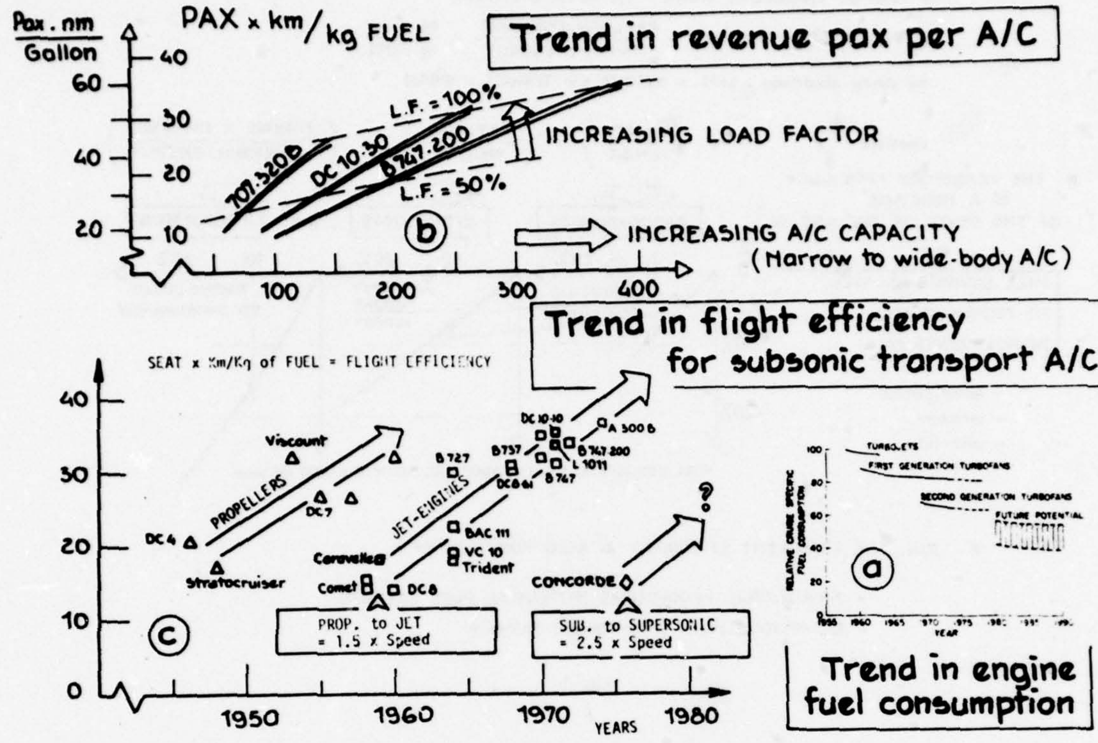


Fig. 2

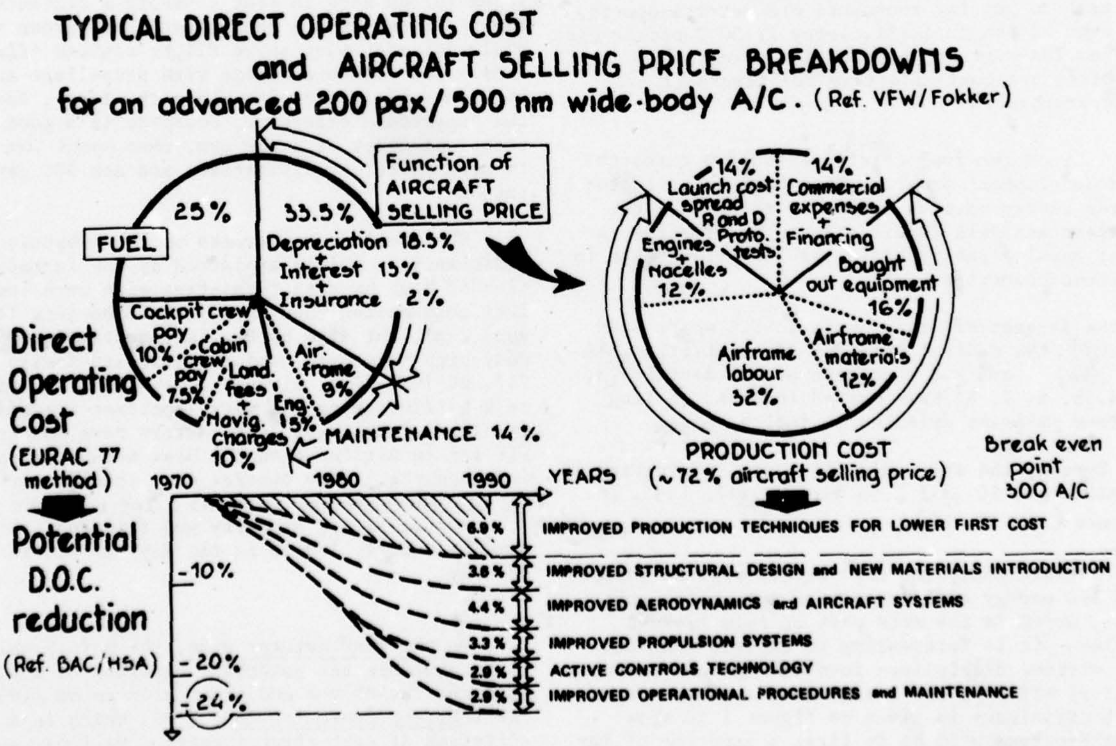


Fig. 3

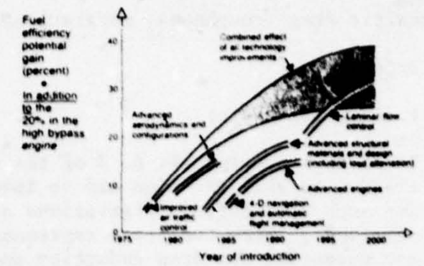
- the largest portion of DOC (33.5 %) comes from depreciation, interest and insurance , which are direct functions of the A/C selling price ; but about 72 % of this selling price is directly connected to the production cost, as detailled on the right graph of figure 3 ; an efficient way of reducing the DOC is to improve the production techniques ; as shown on the lower graph prepared by two British manufacturers [10] , there is a good chance to save about 7 % on DOC in the next two decades by these progress : further gains (+ 17 %) are predicted with various technological and operational improvements, as explained later on.

Returning to the first graph on figure 3, the fuel represents about 25 % of the DOC, and this percentage increases with the fuel cost ; this explains how important are the fuel saving programs for a better economy on future projects.

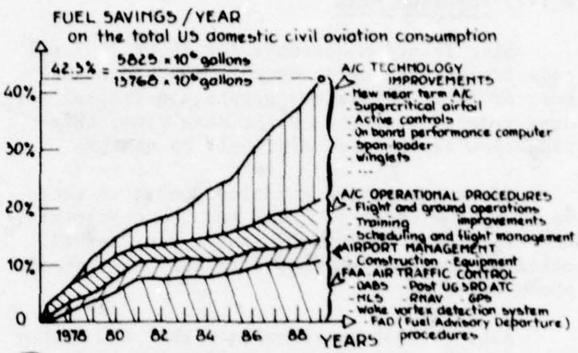
To conclude this introduction, let us have a look, figure 4, on some predictions for fuel savings during the next two decades, as seen by the main American Agencies, NASA and FAA, working on a long range planning : between 30 and 40 % fuel efficiency potential gain seems reasonably possible, the two more important items being :

- the various A/C technology improvements,

- and a better Air Transport system management ; both are quantified in the following sections.



(a) Fuel savings from advanced technology as seen by NASA and Boeing.



(b) F.A.A., aviation energy conservation program

Fig. 4

A) NEW AIRCRAFT DESIGN CONCEPTS

A-1) PROGRESS IN AERODYNAMIC EFFICIENCY

The aerodynamic efficiency of an aircraft configuration can be improved through drag reduction[17,18]; for a subsonic transport A/C, more than 90 % of the fuel consumption occurs during climb and cruise, i.e. in "clean" configuration ; on the diagram of figure 5 [17] are recalled the major drag sources for a subsonic transport A/C :

- skin friction

- induced drag (drag due to increasing incidence)

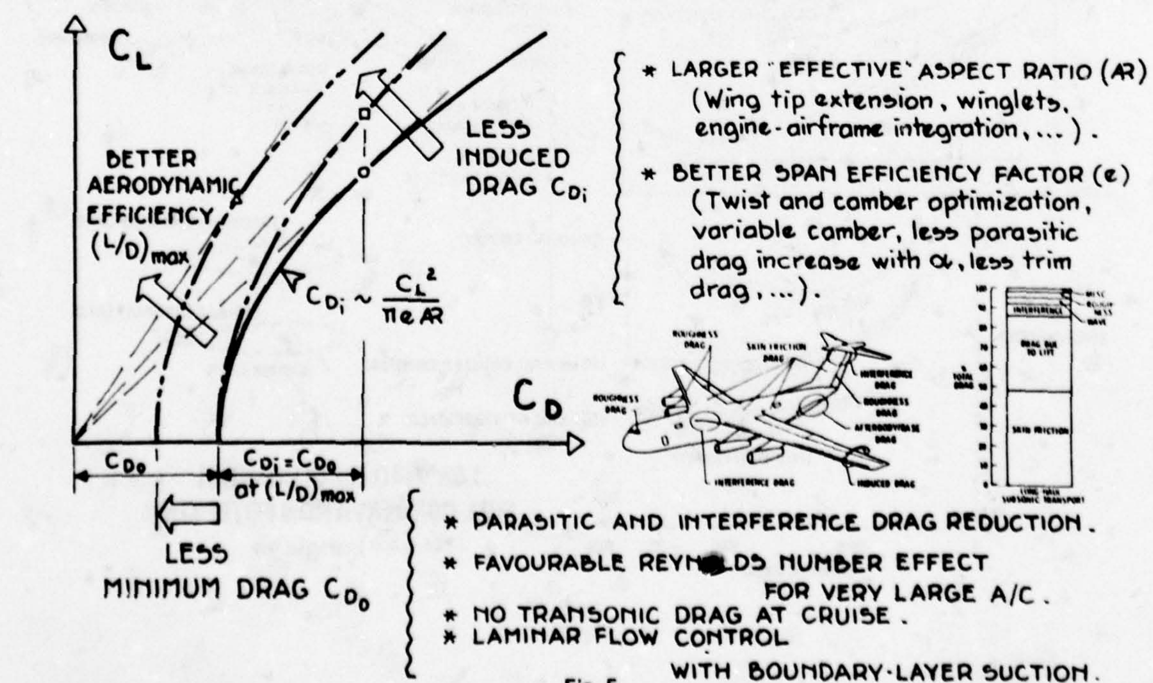


Fig. 5

- parasitic drag (roughness, separations)

- interferences

longitudinal trim, etc...

In fact, approximately 85 % of the total drag are due to skin friction and to induced drag for such transport configurations at cruise conditions ; these two items represent the greatest potential for drag reduction and hence for fuel conservation ; nevertheless, we shall examine briefly the usefulness of reducing each of the various drag components.

A-1-1) FRICTION DRAG

Skin friction accounts for about 50 % of the cruise drag of a current subsonic transport A/C ; it offers the greatest potential for drag reduction, but , at the same time, this reduction is the most difficult to achieve.

Since transition Reynolds number is generally of the order of 3×10^6 and the transport A/C $Re_{\bar{c}}$ in the 20-100x10^6 range, the "normal" state of the boundary-layer is turbulent on the whole airframe.

But, it must be remembered that the turbulent friction drag decreases with increasing Reynolds number ; this trend is very favourable to large transport Aircraft, as shown on figure [6], where a 20 % friction drag reduction is indicated between a small executive jet and a huge future cargo A/C.

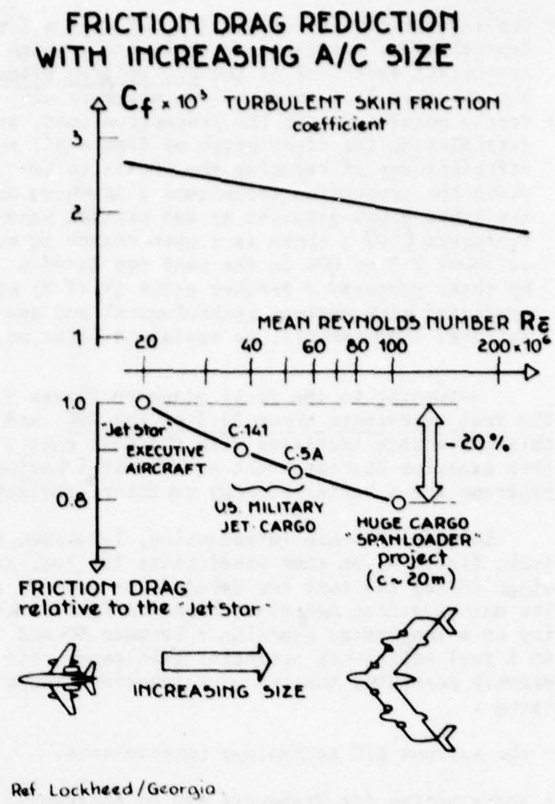


Fig. 6

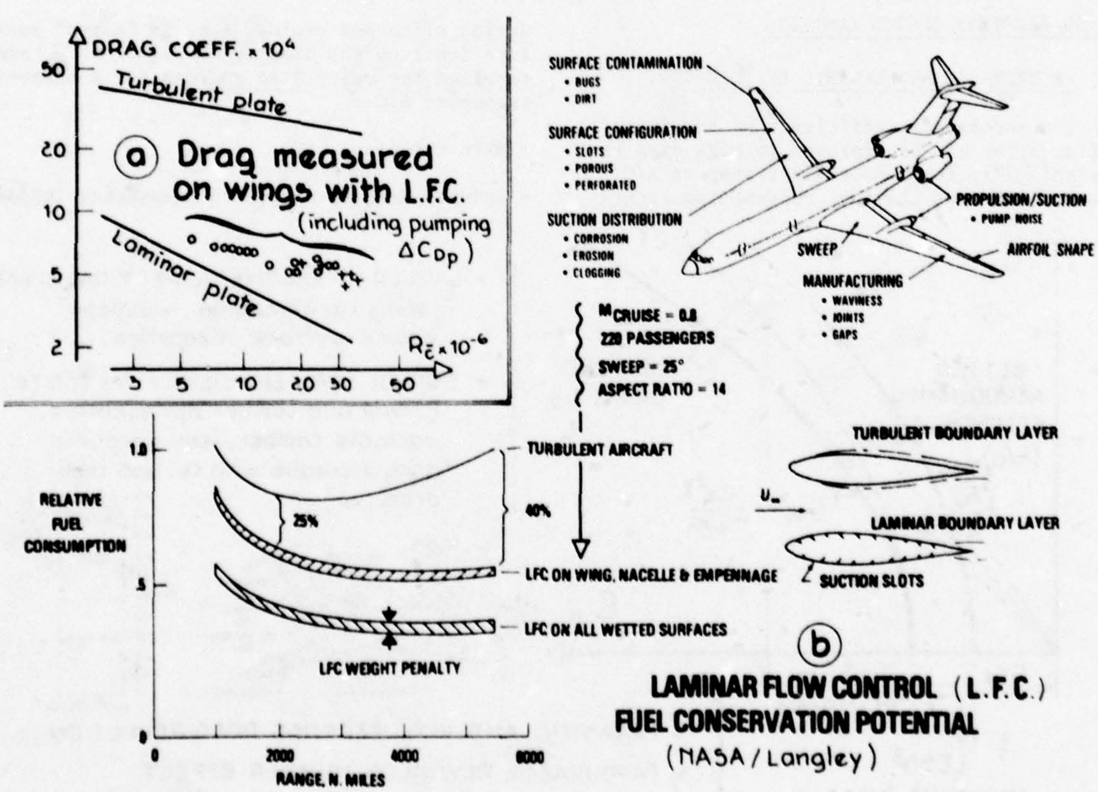


Fig. 7

To delay the transition process, the laminar flow control (L.F.C) by suction through the A/C wing skin is the only technique already proved[17,19] both in wind-tunnel (by Ackeret and Pfenninger, in Zurich as soon as 1946), and in flight (U.S.A.F. Experimental X-21-L.F.C A/C in 1964) ; using suction through many and fine closely-spaced-transverse slots, laminarization to a Reynolds number $Rc \sim 30 \times 10^6$ have been already obtained on wings ; for such laminar flow extension, the drag coefficients are dramaticaly low, near those of a laminar flat plate(figure 7 a) ; then, this concept appears very attractive to reduce the fuel consumption as shown on figure 7b in the case of a NASA long range subsonic transport project : some 25 % to 40 % potential fuel savings, depending upon the range.

But, as expected, such a concept using numerous and fine suction slots, all along the airframe surfaces, leads to very difficult manufacturing (i.e. financial) problems and necessitates a very complex pumping system (i.e. extra weight) ; on the other hand, several factors affect laminar flow, such as surface contamination (insects,...), suction distribution, manufacturing tolerances, wing sweep effect, airfoil shape, location of the propulsion and pumping system (noise effect on transition), etc...(figure 7 b) ; finally, a laminar control would be very difficult on the fuselage (which represents about half the wetted area on a wide-body transport).

However, recent technology advances are included in the NASA A/C energy efficiency program on L.F.C ; for example : woven graphite - epoxy porous surfaces, laser or electron-beam drilling techniques and light weight composite ducting, etc... ; that is why 3 airframe manufacturers are asked to study L.F.C transport configurations projects for the 1990's [1].

To take full advantage of the friction drag reduction, it is desirable at the same time to reduce the induced drag by increasing the wingspan (AR $\sim$ 14 for example) which leads to difficult structural optimization taking account the suction ducts (cf. Boeing proposal : high wing braced with a strut).

To conclude on this controversed laminar flow control, we must say that this concept is only attractive for very long range missions and will be very expensive to manufacture and to maintain (internal complexity), while the operational problems would probably not be welcome to any airline ; however, this concept would be interesting for very long range/high altitude military A/C as a first demonstration before possible civil application ; for example, a Lockheed - Georgia study had shown that application of L.F.C to the wing and empennages of a C-5A Cargo could produce 20-25 % range factor improvement : but, from a cost-effectiveness standpoint, this application would be questionable at ranges less than 6000 nM.

Another way to reduce friction drag is to let the flow stay turbulent and to reduce the turbulent shear ; the possible payoff in this approach is about half the gain possible with L.F.C but less sensitive to operational pertubations ; two concepts are still at the early laboratory stage :

- turbulence control with compliant walls
- slot injection to reduce turbulent friction.

The compliant skins are flexible surfaces made to respond uniquely to the fluid motions in the boundary-layer (maximum skin-friction reduction occurs when the foundamental membrane frequency is about half the peak power frequency in the boundary-layer). It seems too early to predict some application of such flexible surface on an operational A/C. [see 20].

The slot injection concept is much simpler in its principle : the low momentum slot flow, injected to the surface at a low relative velocity (about 30 % of the free stream), alters the velocity distribution in the turbulent boundary-layer and reduces the skin friction ; but, to have a net drag reduction, the skin-friction reduction plus the slot thrust must be larger than the losses due to collecting, ducting and distributing the slot air, plus the slot base drag ; the few results available at subsonic speed show that the local friction drag is about half just behind the slot, and increases rapidly downstream to the conventional turbulent friction value at a distance of about 100 time the slot height [21]; up to now, no systems analysis for A/C applications is available to judge the balance between gains and losses ; two applications seem attractive :

- slot injection on the front fuselage used as the exhaust of a laminar suction system installed on the wing,
- slot injection behind the fuselage cockpit coupled with suction around a truncated base at the rear (to maintain attached flow) ;

again, it is mandatory to estimate the price to pay for pumping and ducting this auxiliary flow.

A-1-2) PARASITIC DRAG

Roughness or excrescence drag is mainly due to local flow separations and vortex formations produced by aircraft surface discontinuities [17] like panel joints, engine inlet contour, gaps around doors, windows and control surfaces, rough surface finish, pressurization leaks, antennae, misrigged controls, etc... Such typical roughness/excrescences represent about 3.5 % of the total cruise drag of the giant C-5A U.S.A.F military transport [22] ; Boeing reported that a pressurized area seal leak (65 cm2) along doors and windows on the 727 could cause about 71.000 Kg increase in fuel consumption per airplane per year [17] ; it would cost $ 61 and a downtime of 4 hours to fix the seal leak. Another example again on a B-727, where a 1-degree sideslip, caused by misrigged control, resulted in a fuel burn penalty of about 108.000 Kg per year (i.e. a loss of about $ 11,000, to be compared to $ 180 and 12 hr downtime to repair the control !).

Another typical parasitic drag often appears on large military cargo A/C, due to separation and vortices adjacent to wing-fuselage juncture and fuselage afterbody door, etc... [23] ; in the case of the U.S.A.F cargo C-141, wind-tunnel tests have shown that redesigning the wing/fuselage fillet strongly improved the vortex flow pattern which gave a 5 % drag reduction at cruise ; and thanks to a better lift distribution, it would be possible to add a 6 foot wing-tip extension without increasing the wing stress, which

would give additional 3 % drag reduction : performance calculations have shown that this 8 % drag reduction can be translated into 8 % fuel saving for each C-141 (figure 8 a), i.e. a total saving of 82000.000 gallons per year for a fleet of 277 C-141 ; on the other hand, the modification cost was estimated at about 11 million dollars, i.e. about one year fuel saving !! It is unfortunate that this improved wing-fillet was not developped, because proposed too late in the program.

As an airplane gets older, a sensible deterioration in its airframe "cleanliness" is experienced, which explains a large part of the fuel consumption increment during the life of an Aircraft ; but, up to the fuel crisis, a general drag clean-up was not yet cost-effective for a company ; certainly, it is no more the case and a large amount of fuel can be saved both on military fleet (tankers, cargo) and commercial fleet by such periodic "clean-up"; a typical "clean-up" exercise have been made recently by Airbus Industry/SNIAS on a production Airbus A-300 (fairing of all steps, slots and gaps) : comparative flight tests before and after cleaning have shown a zero-lift drag reduction of about 4.5% at cruise regime.

Finally the considerable parasitic drag of the various external stores used on military Aircraft can be minimized by a better integration of these loads to the airframe ; a typical example was recently given by Mc Donnell-Douglas with a prototype flight test program on the air superiority F-15 A/C equipped with two fuel pallets ("Fast Pack") mounted at the wing-fuselage interface ; this concept created an additional 4500 Kg of fuel capacity (increase of range/loiter time or payload) without compromising the air superiority capabilities of the basic A/C (and a very small increase of the transonic drag thanks to a clever area-ruling of the packs along the engine nacelles (figure 8 b).

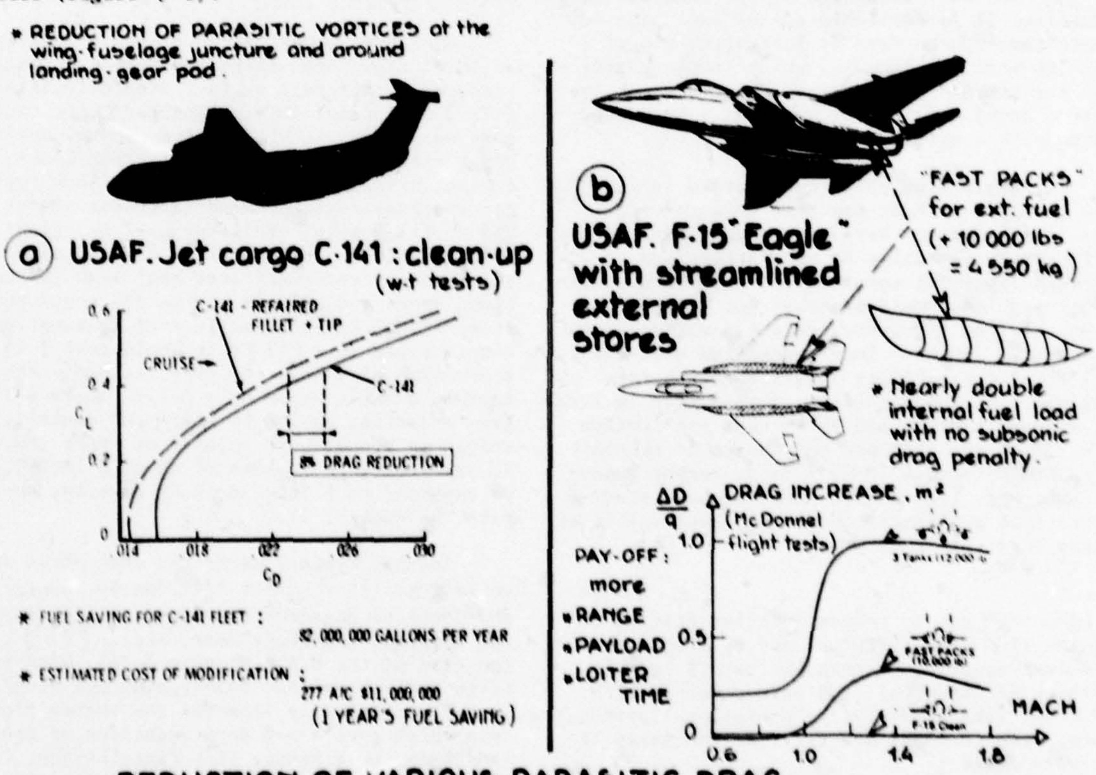
A-1-3) DRAG DUE TO LIFT

We have seen that the polar curve can be written $C_D = C_{Do} + C_{Di}$, the drag to lift, C_{Di}, representing between 40 and 45 % of the cruise drag. At subsonic speed, the drag due to lift is primarily induced drag, but also includes growing participation of parasitic, friction and pressure drags with increased angle of attack, which is reflected in the term, e, span-efficiency factor; when the polar curve is represented as a parabola in the C_L range of interest flown with a clean configuration :

$$C_{Di} = \frac{C_L{}^2}{\pi . AR . e}$$

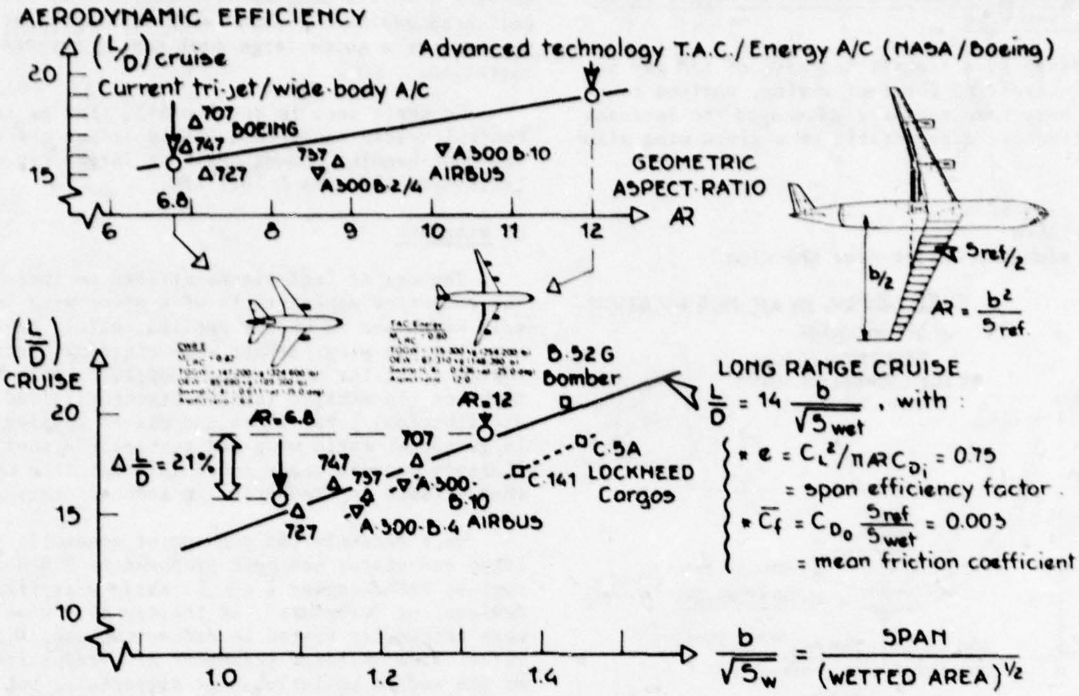
C_{Di} depends upon the spanwise lift distribution over the wing (an elliptical one gives the minimum C_{Di} for a given aspect-ratio) ; but, since induced drag is inversely proportional to wing aspect-ratio AR, the most direct way of reducing C_{Di} is to increase the wing span ; however this larger span introduces increased wing-root bending moments* (and flutter danger), i.e. more structural wing weight for a given thickness (see section A-2) ; one solution would be to increase the wing thickness to cope with these larger bending moments, but it is well known that increasing airfoil thickness ratio increases the transonic drag (or, more precisely, reduces the drag divergence Mach number) for a given wing sweep angle ; we shall see (section A-1-4) that the introduction of the supercritical technology, which permits thicker airfoil section for a same drag divergence Mach number, gives a satisfactory solution [24].

* Very large aspect-ratio, high-wing braced monoplane (AR = 20.2) was produced in France by M. HUREL (HUREL DUBOIS H.D.321/twin-propellers A/C) from 1957 ; outstanding L/D were obtained in flight; the original idea was to use the struts as lifting surfaces.



REDUCTION OF VARIOUS PARASITIC DRAG

Fig. 8



AERODYNAMIC EFFICIENCY OF CURRENT AND ADVANCED A/C

Fig. 9

However, the overall efficiency of an airplane is a function of its structural weight as well as of its aerodynamic efficiency : the optimum aspect-ratio must be a compromise which depends upon the mission (high aspect-ratio is mandatory for a long-range transport) but also on economic considerations (fuel price and/or fuel shortage).

For most of the existing high-subsonic jet-transports in service, the aspect-ratio is around AR = 7, because it was the best compromise, for airlines economy, taking into account the low prices of the fuel during the 1960's ; it is no more the case since the 1973 fuel crisis, and all the designers work now on new projects - or modified versions of existing A/C - which have larger aspect-ratios, up to about AR = 12 or more in some cases.

At first, let's have a look at the cruise aerodynamic efficiency L/D as a function of the aspect-ratio - or in term of wing span and total wetted area parameter : $(b^2/A_{wet})^{1/2}$. This later parameter appears when we look at the minimum drag condition for a long range cruise, i.e. at the maximum L/D given by the tangent to the parabolic polar curve (figure 9) ; in this condition $C_{Do} = C_{Di}$ and :

$$C_{Dmd} = 2\ C_{Do}$$

$$C_{Lmd} = (C_{Do} \cdot \pi \cdot AR.\ e.)^{1/2}$$

and $$\left(\frac{L}{D}\right)_{max} = \frac{1}{2}\ (\pi.\ AR.\ e/C_{Do})^{1/2}\ ;$$

but the zero lift drag C_{Do} depends essentially on a mean friction coefficient $\overline{Cf}$ applied to the wetted surface of the airframe

$$C_{Do} = \overline{Cf}.\ \frac{S\ \text{wetted surfaces}}{S\ \text{reference wing}}$$

and $AR = (\text{Span})^2\ /\ \text{Sreference}$;

thus : $$\left(\frac{L}{D}\right)_{max} = \frac{1}{2}\left(\frac{\pi.b^2.e}{Cf.\ Swet}\right)^{1/2} = k \cdot \frac{b}{\sqrt{S\ wet}}$$

On figure 9 are plotted the cruise values of various large aspect-ratio Aircraft (civil and military transports, bombers) as a function of this parameter $b/\sqrt{S\ wet}$, which shows that most contemporary subsonic civil transports follow the mean curve given by $L/D = 14.b/\sqrt{S}$ wet, when a span efficiency factor e = 0.75, and a mean friction C^t $\overline{Cf}$ = 0.003 are taken. Notice that military cargo (not so streamlined by definition) are below this mean curve.

We have also plotted the values calculated by Boeing [25] for two subsonic transport configurations having the same range (3000nM), the same T.O field length (8300 ft) and the same payload (196 passengers = 18140 Kg)

- the first one is a "conventional technology" (aluminium) three jet (CF-6), wide-body scheme, optimized for minimum fuel (M = 0.82, 3000 nM); the aspect-ratio is only 6.8 and quarter-chord wing sweep is 35° : the resulting calculated cruise L/D is 15.7.

- the second one is an "advanced technology" concept (NASA TAC/Energy study : introduction of composite materials, supercritical airfoils, neutral stability, four advanced turbo-fans BPR = 6, etc...) ; the wing aspect-ratio is very large : AR =12, with only 25° sweep angle ; the cruise Mach number is slightly reduced to M = 0.8 ; the resulting calculated aerodynamic efficiency is L/D = 19, i.e. 21 % more than for a typical contemporary wide-body jet.

Finally, it is important to recall that the optimum lift coefficient increases with the aspect-ratio (as AR $^{1/2}$) , which necessitates to optimize the wing sections for larger C_L to avoid some form-drag penalty [24].

Methods to increase the effective aspect-ratio of a given wing

Since even a small increase of L/D may be very interesting for fuel saving, various concepts have been recently developed to increase the effective aspect-ratio of a given wing planform :

- tip extension
- winglets
- jet momentum effect near the wing

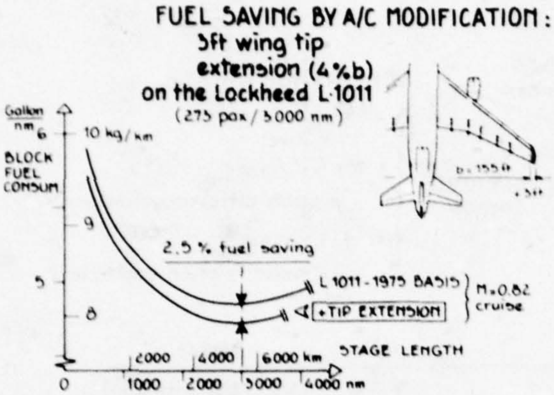


Fig. 10

a) wing-tip extension : a Lockheed/NASA study [26] has shown that a small planar extension at the wing-tip of the L.1011 wide-body trijet (+ 3 feet, i.e. 4 % of the initial span) is sufficient to reduce by 2.5 % the block-fuel used for a 3000 nM mission (figure 10), thanks to the drag reduction during cruise and second segment climb ; but, to cope with the small increase in the root bending-moment due to the larger span, a small reduction in the maximum take-off weight (195.000 to 185.000 Kg) will be required (i.e. a small reduction on the maximum stage length); but in this case, the retrofit on in service L-1011's necessitates only a very simple and cheap addition without wing structural strengthening for a quite large fuel saving pay-off in operation.

We shall see, in section A-3, that an active control system can automatically reduce the extra root-bending moment due to a larger tip extension on the same L-1011 A/C.

b) winglets

The use of "end plates effect" to increase the effective aspect-ratio of a given wing is well known and is widely applied, mainly on small aspect-ratio wing, either with tip-fins (extra yawing stability on a sweep shape), or with tip-tanks or tip-missile (better structural load distribution) ; but these end-plates applied to large aspect-ratio wing had generally a poor efficiency because their added skin-friction more than offsets any reduction in induced drag.

Just recently the concept of specially tailored end-plates has been proposed by R.T Whitcomb at NASA-Langley [24] ; these wing-like devices, or "winglets", at the tip of a wing were originally tested to reduce the wing tip vortex wake on large transport A/C (reduction of the vortex pollution near airports) ; but the preliminary tests analysis have shown that it was possible to optimize the location and the shape of such end-plates located in the strong natural vorticity of a wing-tip ; figure 11-b [27] gives a clear explanation of the capture of this vortex flow to generate a winglet lift force and redirect the flow to diffuse the wing-tip vortex (this explains the name "vortex diffusors" also given to winglets) ; the winglet lift can be directed forward as well as sideways to produce a drag-reducing thrust which exceeds their profile drag ; furthermore, the downwash effect on the main wing, and therefore its drag component due to lift, is also reduced which leads to a net gain on wing (L/D).

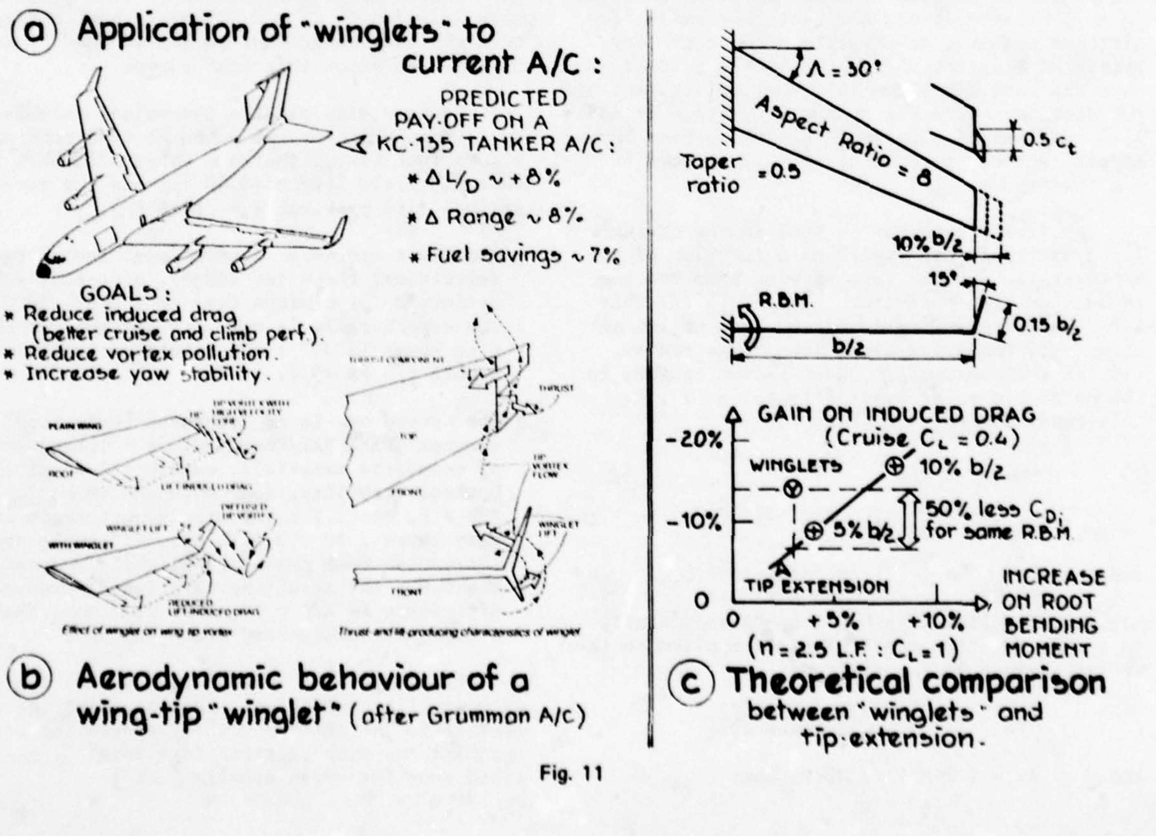


Fig. 11

How this winglet concept compares with a simpler wing tip -extension ?

A theoritical approach of this comparison [28] is given on figure 11-c which compares the gain on the induced drag and the increase on wing root bending-moment, respectively for a upper surface winglet and a tip-extension applied on a aspect-ratio 8 swept wing ; the induced drag reduction is given at the cruise condition (C_L = 0.4), while the increase on root bending-moment is taken at the maximum load factor for a transport A/C (n = 2.5 g , i.e. C_L = 1) it is clear that the winglet concept is far better than a tip-extension for a same extra bending-moment (50 % less induced drag) ; and for the same efficiency (14 % C_{Di} reduction), a tip-extension, of about 8 % of the initial span, gives more than twice root bending-moment.

Notice that root bending-moment is a satisfactory index of the effect on wing structure, the final design objective for a transport A/C being to obtain the best cruise efficiency at the minimum cost in the structural weight.

Several applications of the winglet concept have already been made, both on existing A/C (as a retrofit), or on new projects (maximum winglets benefit will be obtained when the wing can be specially designed to have a tip loading heavier than for a current A/C) :

- winglets on the Boeing KC-135 jet-tanker have been studied by Boeing [29] ; the final design (figure 11 a) is an upper winglet (surface = 2.8 % of the wing semi-span surface and winglet span = 13.5 % of the wing semi-span) which gives a 14 % reduction on C_{Di} at cruise conditions (M = 0.77, C_L = 0.43) ; a 7.8 % gain on L/D is translated in a 8.1 % increase on the range factor (8720 nM versus 8065 nM) and finally a 7 % fuel savings for a typical long range mission. The production "retrofit" winglet weight would be 430 Kg (0.3 % G.W), which includes a slight structural modification near the wing tip ; prototype winglets will be flight tested, fall 1978, for U.S.A.F.

- Similar study, but with upper and lower winglets, have been made by Mc Donnel-Douglas around their existing transport A/C, which gives the following fuel savings for (specified) typical values of their stage length :

  DC-8-61, Δ block-fuel = - 1.74 % (800 nM)
  DC-9-10, - d°- = - 1.31 % (300 nM)
  DC-10-10, - d°- = - 4 % (870 nM)

  More details on the DC-10 modification with the winglets are given in [30].

- Grumman plans to put such winglets on his new executive A/C "Gulfstream III", which permits a 8 % reduction of the wing area for the same performance as with the conventional wing.

Finally it is important to recall that such winglets give complementary advantages :

- a better (L/D) in climb, which is very important for one engine-out capability ; in fact, it was the primary goal of winglets installation on the Israel Industries "ARAVA", twin-prop STOL A/C ; in the take-off configuration, the induced drag is reduced by 20 % during the climb, which permits to satisfy the F.A.R rule with "one engine-out" at the full T.O weight ,

- a wing span smaller than wing-extension, which simplify the parking problems on airports,

- a reduction of the vortex-tip pollution from large A/C near airfield (less terminal area separation, i.e. fuel savings),

- increased yawing stability when applied to swept-back wings.

We shall see in section A-5, that the vertical fins at the tip of a flying-wing without taper ("spanloader" cargo concept) are the most effective "winglets", that increase tremendously their effective aspect-ratio, i.e. their aerodynamic efficiency for a modest geometric AR. (see figure 33).

c) <u>jet momentum effect near the wing</u>

For those transport A/C equipped with engines attached to the wing, a very large momentum is exhausted near the wing surface which induces supervelocities by entrainment effect ; how to use this strong interaction to reduce the drag-due-to-lift ? Several ways have been explored in wind-tunnel, some of them will be analysed in section A-4-1.

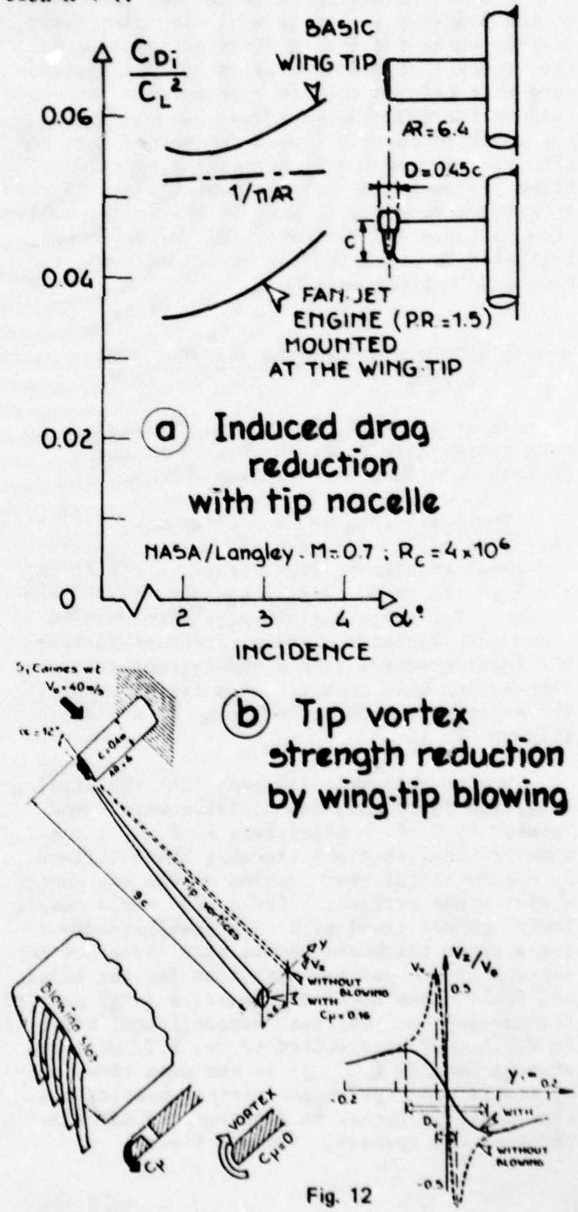


Fig. 12

With the tip-mounted engines scheme, the objective is to reduce the wing-tip vorticity, i.e. C_{Di}, by the cancelling effect of high-energy exhaust of a tip-mounted fan-jet engine ; such a concept have been tested at NASA-Langley [24 and 18] on a semi-span untapered unswept wing (AR=6.4) with a simulated fan-jet by-pass ratio 8 engine at the wing-tip (Mach 0.7, fan-jet P.R = 1.5) ; figure 12a shows that the powered fan-jet reduces the induced drag by about 30 % over that for the basic wing-tip model, i.e. below the theoretical minimum $1/\pi$ AR ; a part of the benefitial effect is due to the "end-plate effect" of the fan-engine (about 40 % of the previous gain is obtained with a hollow duct having a same diameter) ; in fact, the jet wake completely destroys the concentration of the tip vorticity, and it might be expected that a larger effect would be obtained by prerotating the fan exhaust.

Such a concept was used on the production "Noratlas", a French military twin-prop cargo A/C, equipped with two small jet-engines Turbomeca Marboré at the tip, mainly designed to increase the take-off and climb performances, which were much improved indeed.

Another scheme to conteract the formation of the wing-tip vortex is a blowing slot along the tip whose the jet is directed opposite to the vortex ; figure 12 b illustrates a preliminary test made on a large aspect-ratio semi-span wing in the ONERA/Cannes wind-tunnel to demonstrate the complete destruction of the vortex core and also the net gain on C_D' net including the small blown jet momentum ; such a device would be very attractive to reduce a part of the vortex pollution on large A/C (in fact, this research was initiated for reducing the vortex wake interaction on a helicopter rotor).

A-1-4) INTRODUCTION OF THE SUPERCRITICAL TECHNOLOGY

Since about fifteen years, the advance in wing design have followed an "evolutionary" process more than a revolution. [31 and 32].

The basic idea was to design a wing section able to develop on its upper surface an extended local supersonic flow without a too strong shock at the rear, causing boundary-layer separation ; for that, a rapid expansion must be developed around a pronounced curvature near the leading-edge ; then a quasi-isentropic recompression must take place to reduce smoothly the supersonic Mach number ahead of a weak shock (figure 13).

Due to this velocity peak near the leading-edge, the first advanced airfoils were named "peaky" by N. P. L scientists in U. K. ; the supercritical sections are also characterized by a substantial rear loading due to aft camber, a flat upper surface, a large nose and a cusped lower surface ahead of a thin trailing-edge ; for a given thickness ratio, this shape accomodates a wider spar and more room for the internal fuel. Since about ten years, a large part of the development of these supercritical airfoils in U.S.A must be credited to Dr. R.T. Whitcomb at NASA-Langley [33]; in the mean time, considerable progress on theoretical predictions were realized thanks to computerized calculations of the transonic Viscous flow.

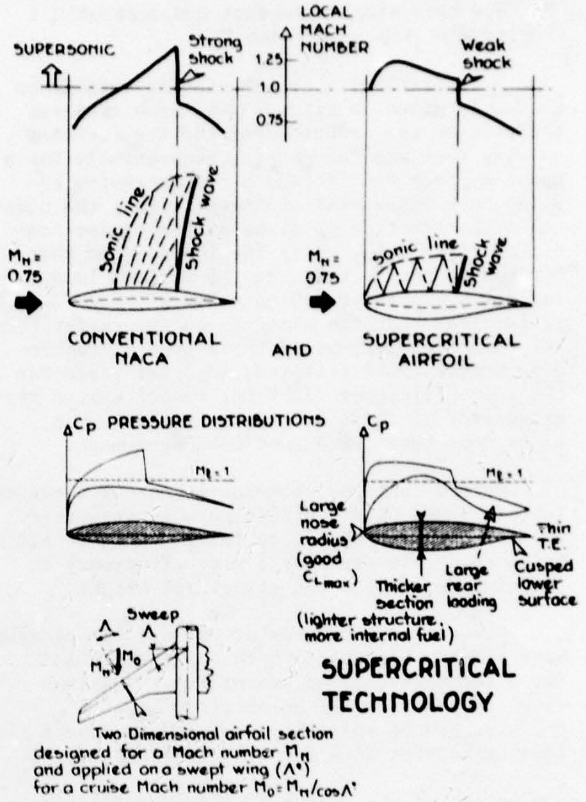


Fig. 13

The main advantage of these advanced airfoils is a higher drag divergence than a conventional section (NACA family) for a given thickness ; on the other hand, this concept can be utilized to increase airfoil thickness for a given drag divergence Mach number ; thus, two types of applications are possible :

a) Keeping the same cruise Mach number, (figure 14 a). The wing thickness can be increased :

- to reduce the structural weight for a given planform,

- to increase the aspect-ratio for a given wing weight (better aerodynamic efficiency L/D)

- and to put more internal fuel.

Another alternative is to reduce the wing sweep to have better high lift capability and a better L/D at low speed ; in fact, the optimum configuration is generaly obtained by a compromise between thickness, aspect-ratio and sweep angle, taking into account the structural weight and the global aerodynamic performances suitable for a given mission.

b) Increasing the cruise Mach number (figure 14b) was the original goal of the supercritical technology, before the fuel crisis ; in fact, a near sonic configuration (supercritical F8-U) was flight tested by NASA and several transport A/C projects were studied which have shown improvements on the range factor, and of course on the block speed, giving more productivity ; but the high manufacturing price of such sophisticated aircraft (including a difficult fuselage area ruling) and its poor fuel usage more than offset its small speed advantage.

SUPERCRITICAL TECHNOLOGY APPLICATIONS

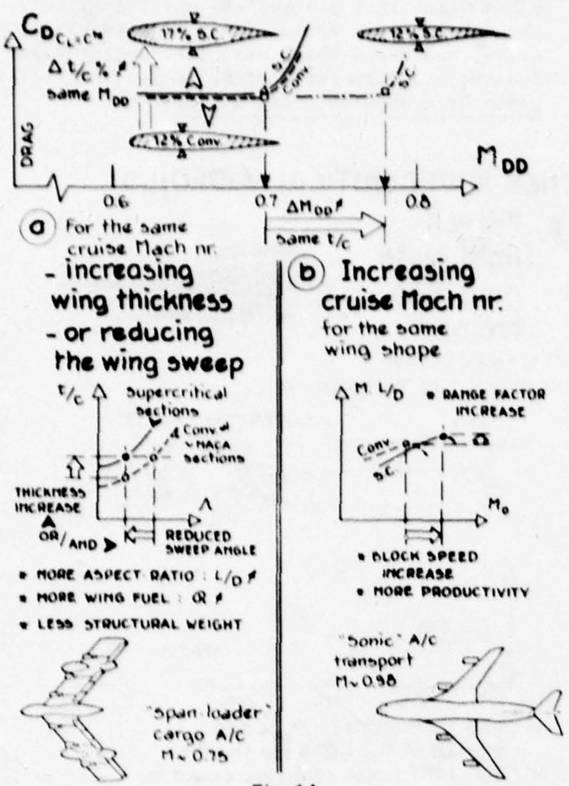


Fig. 14

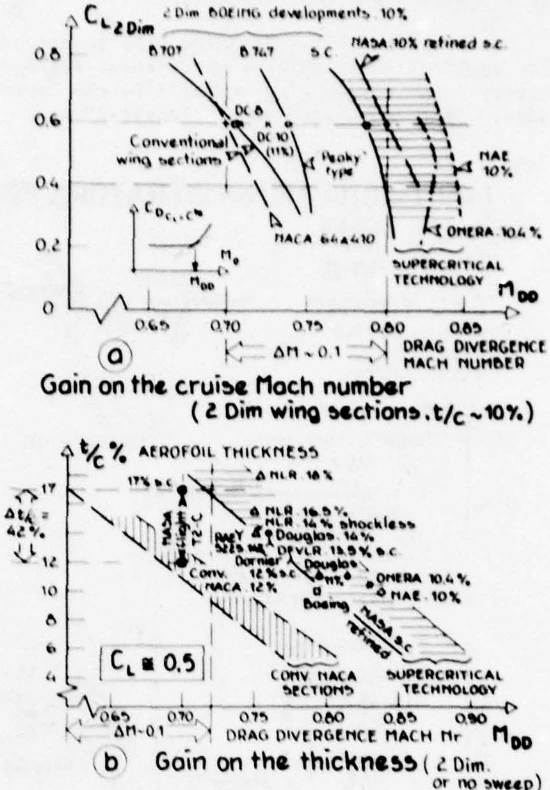


Fig. 15

The state of the art on supercritical airfoils, from published 2 Dimensional results, is given on figure 15 : the upper curves give a good overview of the progress on the drag divergence Mach number made in airfoil design from the first jet-transports, to present wide-body jets and to new "supercritical" current projects. The lower diagram gives the drag divergence Mach number (for a given $C_L = 0.5$) as a function of airfoil relative thickness, respectively for conventional and for supercritical sections developed recently by various laboratories and firms :

- for a given thickness, the gain on the limit Mach number can reach about $\Delta M = 0.1$,

- for a given limit Mach number M_{DD}, a supercritical section permits about 50 % more thickness than a conventional one ; this last result is very impressive when transferred in wing structural weight saving : for example, increasing the wing thickness from 12 % to 18 % on a typical twin-jet/cargo transport Aircraft (GW = 75.000 Kg, AR = 10, $\Lambda = 25°$) reduce the wing structural weight by about 25 %, i.e. more than 3 % of the gross weight.

To validate these impressive gains obtained in wind-tunnels on very thick supercritical sections, two experimental unswept "trainer" A/C were flight tested with the same technique (existing conventional wing covered by a plastic "glove" with new supercritical shapes) ; figure 16 illustrates some typical results obtained on a T-2C trainer in U.S and on a T-33 trainer in France, respectively :

a) in 1969, a 17 % thick supercritical section designed by Rockwell/colombus for NASA [24] was fitted to the production T-2C wing having conventional 12 % thick NACA sections : comparison of the drag measured in flight on both configurations shows that they have almost exactly the same drag divergence Mach number ($M_{DD} = 0.7$ at $C_L = 0.5$) ; moreover, the buffeting onset is improved in all the flight domain with this very thick supercritical section and the low speed maximum lift coefficient in flap-up configuration is improved by 50 % !

b) More recently, a 17 % thick supercritical section designed by Aerospatiale/Suresnes in 1975 was fitted to a T-33 wing equipped with conventional NACA 13 % thick sections (French MOD/ONERA and Civil Aviation program) : here again the flight tests [34] have confirmed the wind-tunnel predictions : about the same drag divergence Mach number ($M_{DD} \cong 0.76$ at $C_L \cong 0.3$), for both configurations, but also, excellent maximum lift ($C_{L\,max} \cong 1.65$) and handling qualities at low speed and good aileron response up to M_{DD} for the supercritical configuration.

A typical example of the aerodynamic design of thick wing for a swept subsonic transport is given(figure 17) from a recent theoretical and experimental study by NLR [35]: the main objective of this design was to obtain an almost shock free supercritical flow on the upper surface of a AR = 8, 20° swept wing fitted with very thick supercritical sections (18 % at the root, 15 % at the tip) for design Mach number M = 0.75 at $C_L = 0.45$; comparisons between predicted and wind-tunnel measured pressures in 3 dim. flow are in very close agreement and the drag divergence obtained in wind-tunnel ($Re = 2.5 \times 10^6$) is exactly as predicted ($M_{DD} = 0.75$).

It must be remembered that a typical short haul A/C still in service, having about the same cruise Mach number = 0.75, and fitted with a 20° swept wing must have much less thickness

(12 % conventional NACA sections).

We shall see later (section A-5) an attractive application of thick supercritical sections to very large flying wing cargo A/C, the "spanloader", and to various more "classical" near-term transport Aircraft projects (fig. 28-34) : substantial fuel savings are obtained mainly through a global optimization of wing aspect-ratio, sweep and thickness, i.e. better aerodynamic and structural efficiencies indirectly given by a supercritical design.

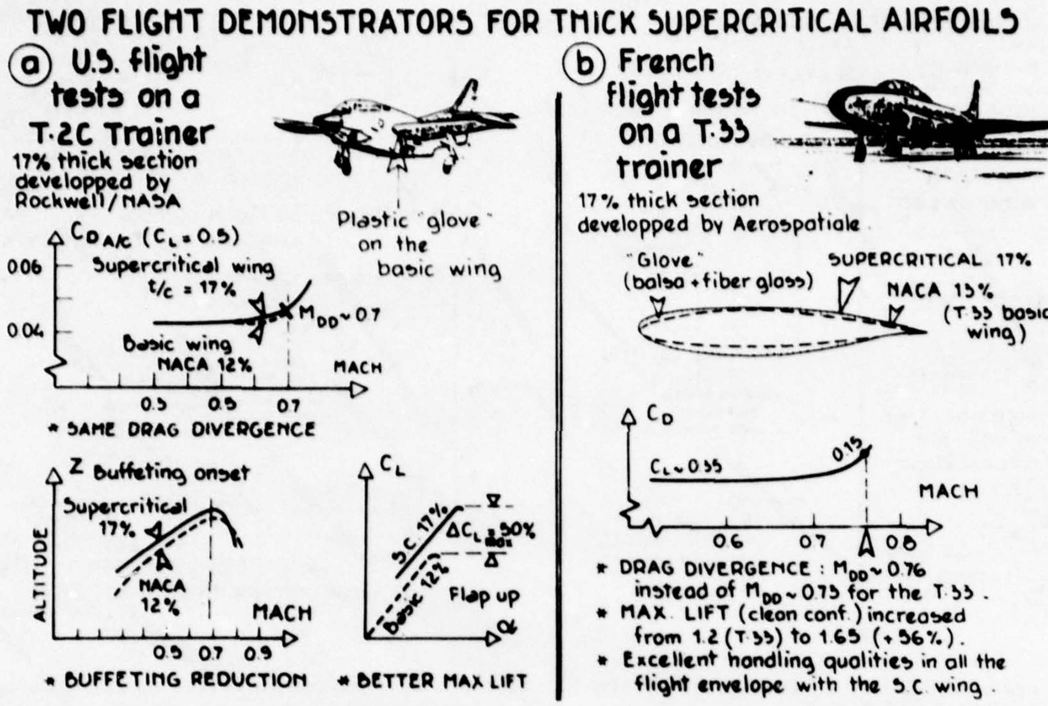


Fig. 16

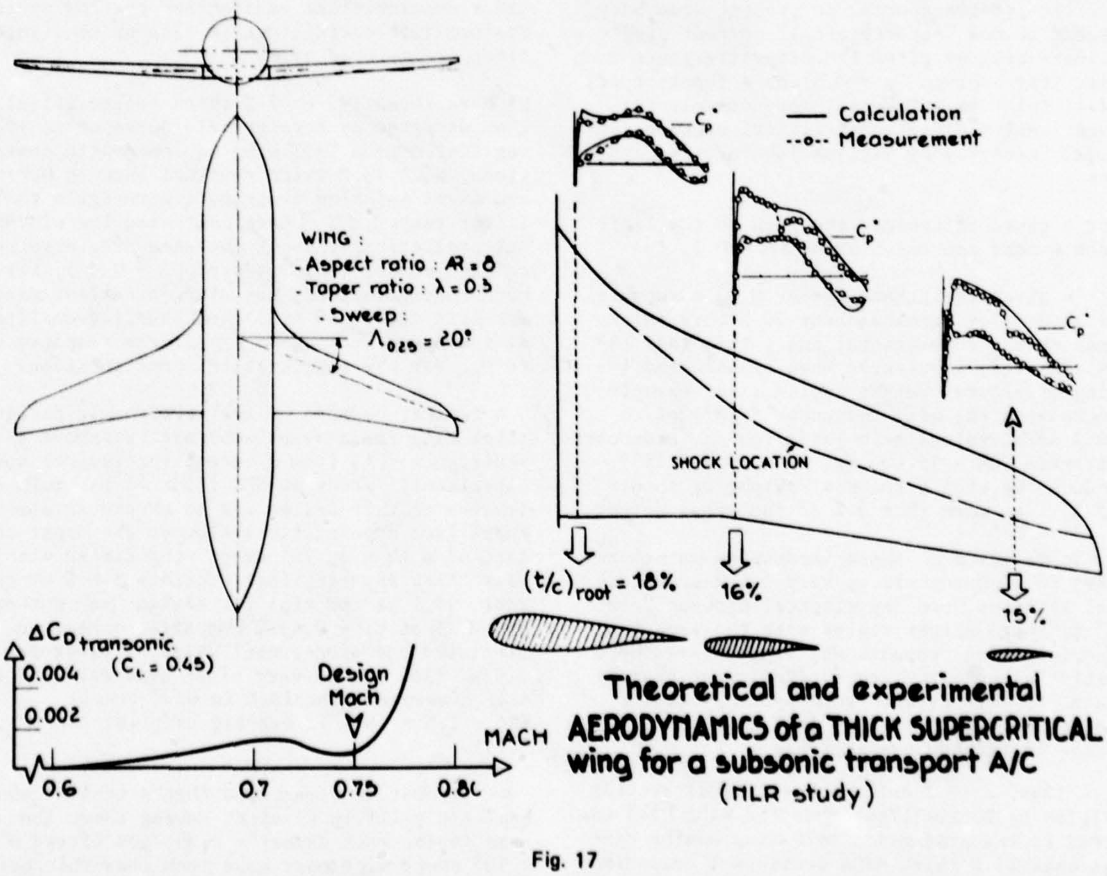


Fig. 17

A-2) PROGRESS ON STRUCTURAL EFFICIENCY AND INTRODUCTION OF COMPOSITE MATERIALS

By the use of improved structural airframe design (computer programs for structural optimization) and new materials (particularly composites), up to 25 % reduction in airframe empty weight may be possible, which would translate into fuel savings of 10 to 15 % [36,37], as pictured on figure 18 for the next fifteen years A/C designs.

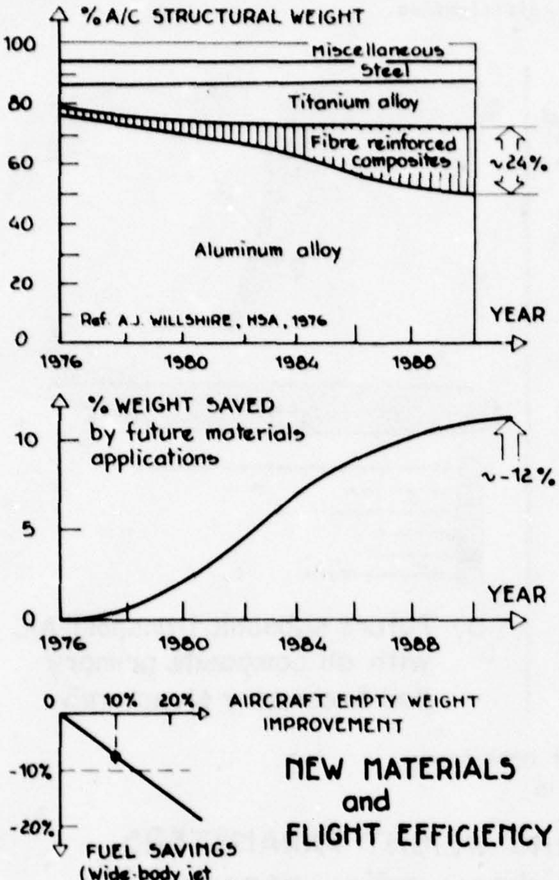


Fig. 18

At first, advanced structural concepts and new manufacturing techniques [6] will make a large contribution to reduction of airframe cost and weight (less structural components, use of integrally machined panels, bonded metal honeycomb, superplastic formed diffusion bonded titanium, etc...).

Furthermore, new advanced "super-pure" aluminium alloys will permit significant reduction on structural weights-as large as 8 to 10 % [4] -for the 80's projects.

Another major technological development of recent years is advanced composite materials made with graphite, boron or kevlar fibers in an epoxy matrix, which offer much superior ratios of strength and stifness to density [7]; but the principal barrier to an extensive use of composite materials for the next generation of transport A/C is the lack of experience on their durability and maintenance problems for a 50.000 flight hours life extended on a 20 years period (we have already accumulated more than forty years experience on Aluminium structures, both in service and in laboratory tests) ; that is why the first step to obtain the necessary experience under actual service conditions has been to begin with secondary - non critical- structural components (spoilers, ailerons, fairings, rudders, etc...) or with use of composite reinforcements applied on metallic primary structures (to extend the life of military A/C, as on a C-130 cargo A/C). Such demonstrations began about five years ago in several countries, the strongest technological effort being made by the U.S.A.F. Material Laboratory and by NASA (composite primary A/C structures, a ten-year program extented up to a complete wing primary structure, [1]).

In those conditions, for the next transport A/C generation of the early 1980's, the use of composite will be restricted to secondary parts as floor beams, trailing-edge surfaces or fairings (also applicable as retrofit items on in service A/C) ; then, the fuel reduction to be achieved on first phase would be rather modest: for example, on a typical wide-body transport (L-1011 or DC-10), a 2500 Kg weight reduction permits about 1 % fuel savings ; then one needs about 12500 Kg of composite structure application (with an estimated 20 % weight reduction Viz. aluminium structure) to have this 1 % fuel savings in operation. Consequently, the maximum fuel savings for the next A/C generation would be between 1 and 2 % [5], but it is a part of a mandatory learning cycle.

In fact, the real pay-off will be their use on primary structures : for example, a composite wing-box structure applied on a new A/C (of the B-747 class) might save about 7500 Kg - equivalent to 75 passengers payload or about 3 % savings in block-fuel ; but it is too early for a sound manufacturer to launch now such composite construction into a non-removable primary structure with a risk of ageing phenomena [4].

If we look now to far-term introduction of composite materials into transport A/C projects, it seems interesting to briefly summarize some trends from general studies asked by NASA to Boeing [38] : during the course of a parametric analysis, they have looked at the structural weight penalty to improve the aerodynamic efficiency through an increase of aspect-ratio for a Mach 0.8 long-range wide-body advanced transport A/C (200 passengers, on a 3000 nM stage length, where about 80 % of the block-fuel is consumed during cruise) ; the wing shape is given : sweep : $\Lambda 1/4 = 30°$, and supercritical airfoil thickness from 15.5 % at the root to 10 % at the wing-tip ; figure 19 a gives the wing weight, respectively for a conventional aluminium structure and for an advanced composite structure (with - 10 % and - 25 % weight savings) as a function of the wing aspect-ratio (from 8.6 to 12) ; we have already seen (section A-1-3) increasing aspect-ratio is a very powerful way to increase the fuel usage (here 6 % savings from AR = 8.6 to 12), but a full benefit of composite materials is also very beneficial : 4 % fuel savings for a 25 % advanced composite structure ; in this later case, figure 19 b gives some details on such a long-term transport A/C structure :

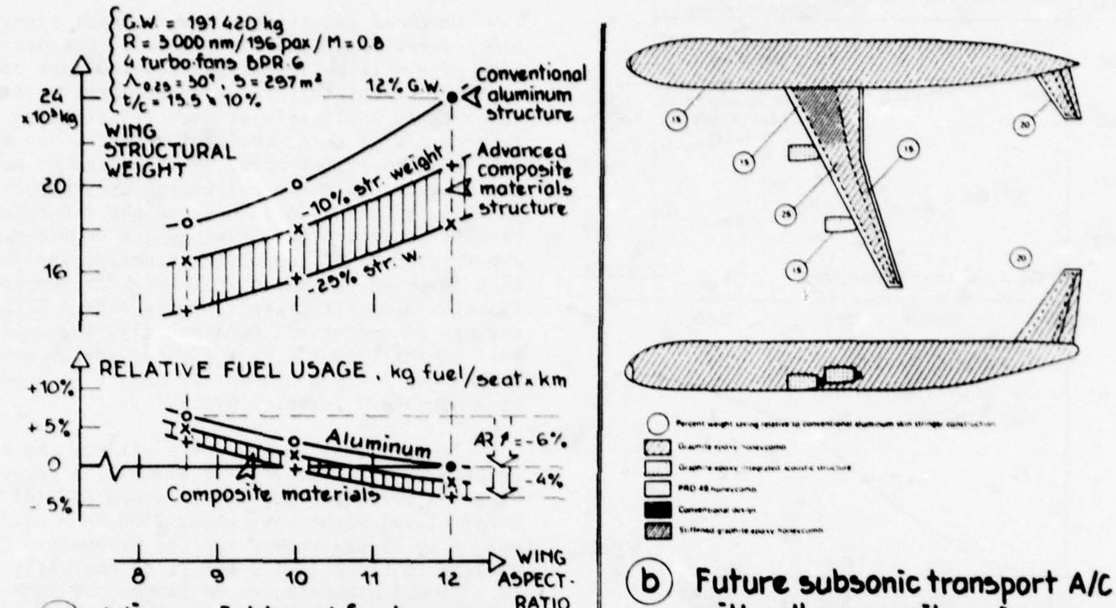
- graphite epoxy honeycomb for the wing, where advanced composite material is particularly advantageous for a high aspect-ratio wing-box (designed for gust and flutter considerations rather than for maneuver),

- graphite epoxy for fuselage and empennage primary structure, for all control surfaces, and for propulsive nacelles with integrated acoustic treatment ; all figures in % are given relative to aluminium skin stringer construction [38] .

To conclude this section, it seems interesting to point out the structural wing weight sensitivity to geometric parameters, as shown on a typical modern wing design (figure 20) :

- wing thickness : thicker airfoils lead to a sensible weight reduction for given AR and sweep,
- aspect-ratio : increasing AR is very detrimental to the wing weight if t/c is not increased,
- wing sweep : the structural weight increases slowly with the sweep angle.

Again, it is clear that the introduction of the supercritical technology is the solution to improve both the structural and the aerodynamic efficiencies.



(a) Wing weight and fuel usage versus aspect ratio and structural technology.

(b) Future subsonic transport A/C with all composite primary and secondary structures.

Ref. NASA/Boeing

Fig. 19

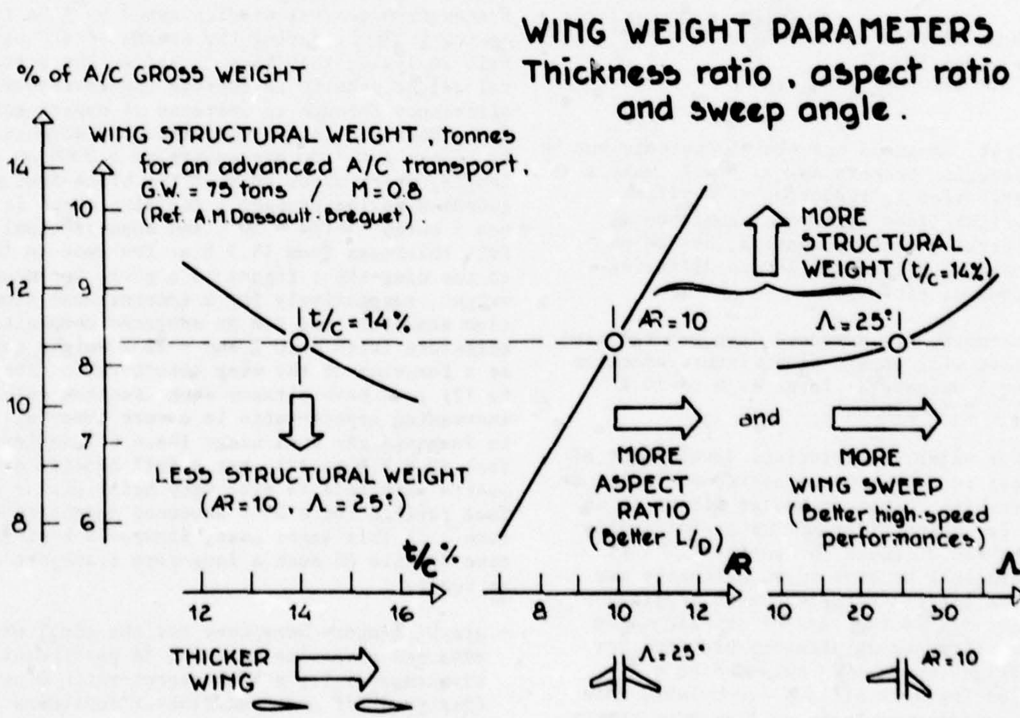


Fig. 20

A-3) PROGRESS ON ACTIVE CONTROL TECHNOLOGY

In this section,we shall detail some active control systems which will be a small part of the integrated digital systems installed on future transports [5] ; we have already some ideas about the avionics technology available in the next twenty years [39], which probably will be a key to fuel savings, because its large impact on better operational procedures (see section B-3) ; this integrated digital system will monitor :

- fully digital automatic flight controls, plus central air-data systems,
- fully automated three-dimensional navigational flight-path control,
- attitude/heading reference systems using laser gyros,
- autoland capability for category III.all weather landing,
- optimized profile navigation (4 dim.) for fuel savings,
- digital data busses (using also fiber-optic technology, for in-board transmissions),
- flight operations controlled from the ground through data-link communications,
- propulsion control and A/C fuel management,
- and finally, active airframe control technology (ACT) based on a fly-by-wire installation.

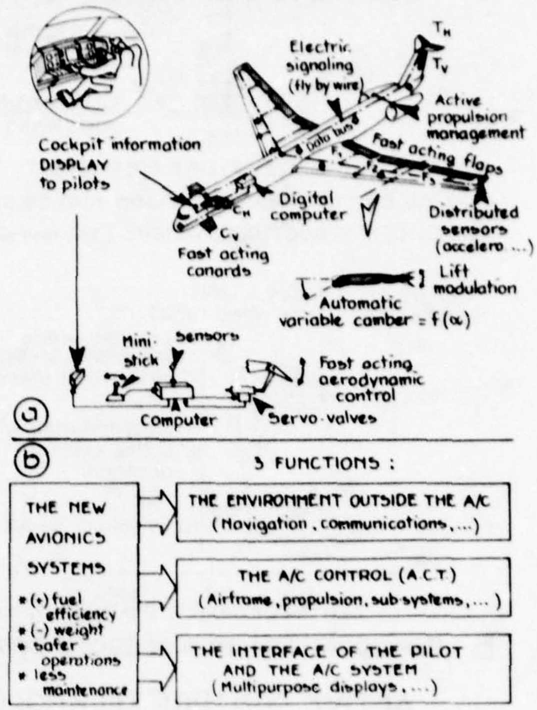
For a transport A/C, the most important requirement for a safe application of active controls is an extremely high level of reliability in all the components of the system [1], and particularly the computers which must be capable of failure detection, identification and recovery.

The main goals of active control technology for transport A/C are [40,41 and 42] :

- relaxed static stabilities,
- maneuver load control,
- ride improvement and gust alleviation,
- flutter mode control,
- direct lift and side-force control,
- center of gravity control,
- variable camber and flight envelope limiting.

Some of these items are directly, (drag reduction) or indirectly (weight reduction) attractive for fuel savings, either for the next transport A/C generation and even derivatives of existing A/C, or more generaly for longer-term projects. Figure 21 gives a sketch of such idealized ACT transport which highlights the importance of the new avionics systems.

ACTIVE CONTROL TECHNOLOGY
ON FUTURE TRANSPORT A/C



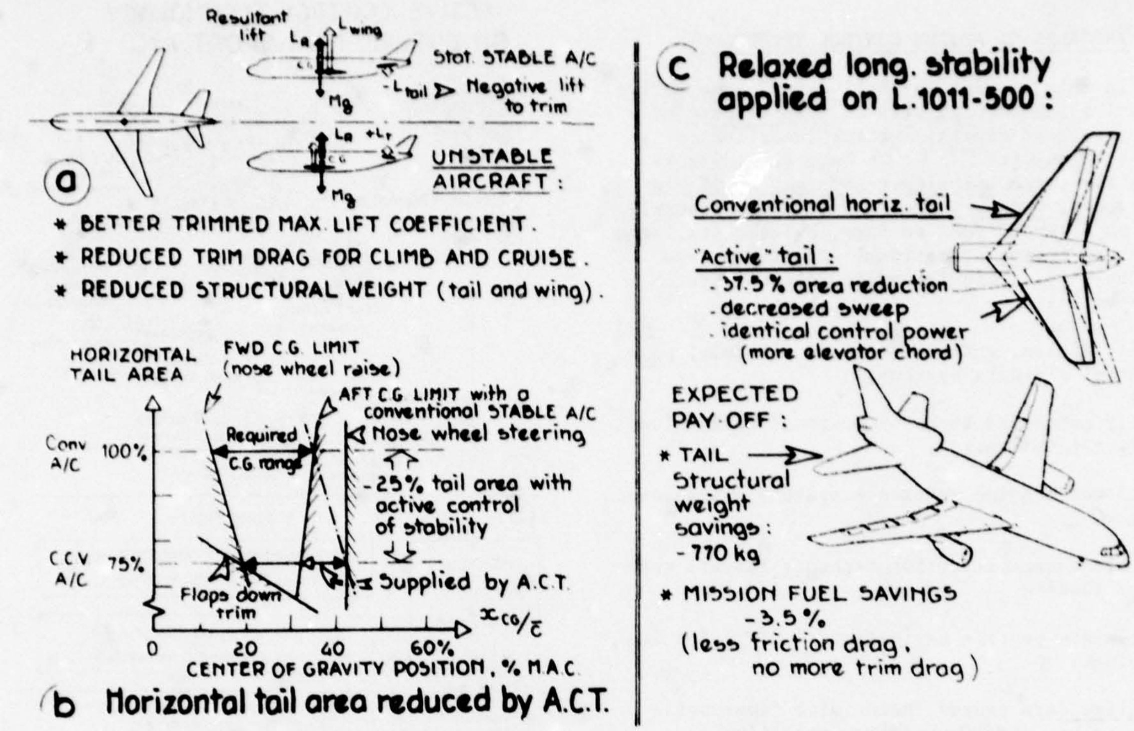
Ref NASA Fig. 21

A-3-1) RELAXED STABILITY

Several current commercial transport and military A/C have already some stability augmentation systems (yaw damper are already in service on many *existing A/C*) ; *but, here, the main* objective will be to reduce the tail size as explained on figure 22-a for a conventionnal A/C configuration ; thanks to a reduced trim drag in cruise and in flap-down configurations, and to a reduced tail weight,.a "snowball effect" leads to a smaller A/C, i.e. lessdrag, and finally to a sensible fuel savings.

On a transport A/C the center of gravity range is determined by passenger and freight accommodation ; figure 22-b explains how the same C.G range can be obtained with a large horizontal tail surface reduction thanks to stability augmentation ; however the maximum aft C.G location, i.e. the amount of controlled instability is generally limited by control-power and by nose wheel steering (for an imposed main undercarriage location, generally fitted to the wing) ; in the figure 22b for example, about 7 % aft movement of C.C leads to a 25 % reduction on the horizontal tail area, with the same required C.G range.

A practical application of relaxed stability is already planned by Lockheed for its "Tristar" derivative, the L-1011-500, which will incorporate both a tip-extension (see next section A-3-2), and a reduced horizontal tail surface [5]; figure 22-c shows that the new horizontal tail has a 37.5 % area reduction, less sweep, but the same longitudinal control power ; the combination of the reduced structural weight (-720 Kg, i.e. about 0.4 % of its gross weight), and of friction and trim drag reductions,leads to a 3.5 % fuel savings for the standard mission of this wide-body A/C.



ACTIVE CONTROL TECHNOLOGY APPLIED FOR RELAXED STABILITY

Fig. 22

ACTIVE CONTROL TECHNOLOGY FOR MANEUVER LOAD CONTROL

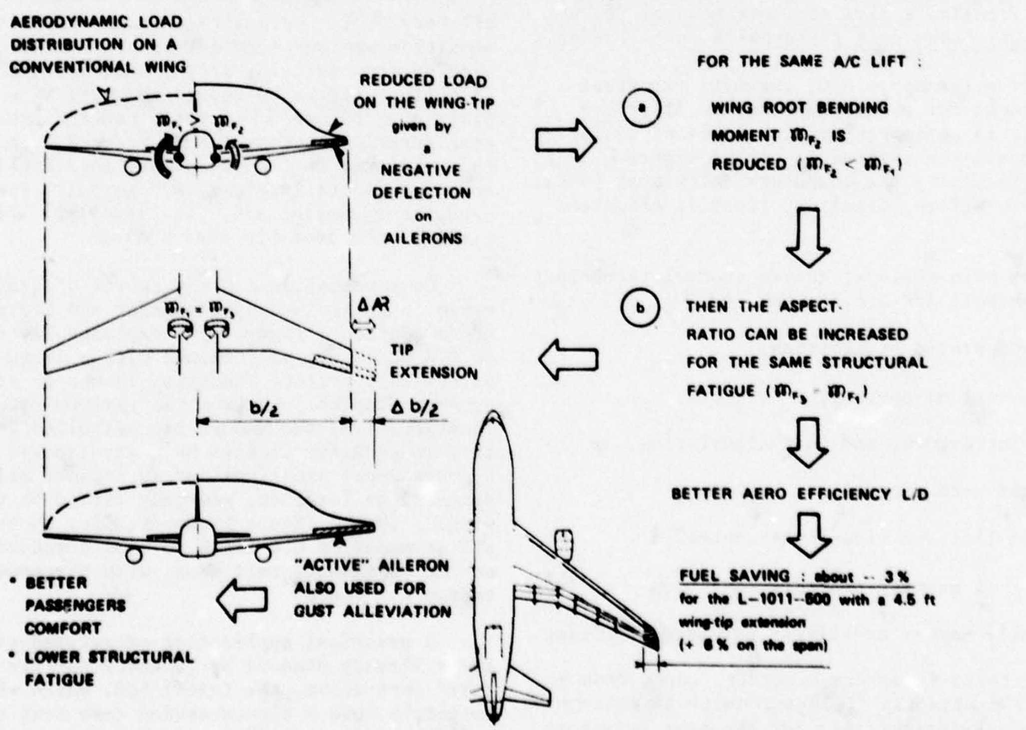


Fig. 23

Relaxed stability has been successfully flight tested on several military A/C (B-52/CCV, F-4/CCV, YF-16, etc...) ; during the B-52/CCV study, Boeing has calculated that a new bomber having the same long-range mission (6430 nM), would have a take-off gross weight of 175 tons instead of 204 tons for the current production B-52, i.e. a 14 % weight saving.

The controlled longitudinal instability is particularly beneficial on a tailless configuration, as it will be shown (section A-7) for the French experimental Concorde n° 1.

In principle, the fin size can be reduced in a similar manner thanks to an active control on the yaw mode, the limitation beeing often

the yawing moment power needed to trim a wing-pod- engine failure.

A-3-2) MANEUVER LOAD CONTROL

The basic concept of maneuver load reduction is illustrated on figure 23 - a : the spanwise aerodynamic loading of an efficient wing is usually near-elliptical, as shown on the left-side of the first sketch ; to reduce the wing root-bending moment during a maneuver, active ailerons are symmetrically up-deflected, proportionally to the angle of attack increase, in view to obtain less load on the wing-tip, i.e. a smaller root-bending moment for the same global load (right-side upper sketch).

The pay-off of this concept was demonstrated in flight [41] on the U.S.A.F experimental B-52/CCV (40 % reduction in wing root-bending moment per g for a Δn = 1g maneuver), and on the U.S.A.F cargo C-5A (30 to 50 % bending moment reduction throughout the flight envelope).

These gains can be used :

- either to reduce the wing structural weight (- 5 % in design gross weight of a large bomber/B-52 class)
- or to improve airframe life (as proposed for the C-5A)
- or to increase the nominal design weight without wing structural modifications for an existing production A/C.

But, because of fuel crisis, a cleverer approach is a tip-extension (figure 23- b) in an amount *which just restores the bending moment at the* original design value ; Lockheed plans for 1980's a modified version of its L-1011 Tristar with such an active aileron system which permits a 9 ft tip-extension (about 6 % of the original span) without structural modification at the wing-root [5]; a larger aspect-ratio improves the aerodynamic efficiency and leads to a predicted 3 % fuel savings ; positive and negative symmetrical active aileron deflection is also used to damp out the first elastic wing bending response for reducing wing gust loads (better passenger comfort) ; we have seen previously that this same project will be fitted later with an active horizontal tail to insure relaxed longitudinal stability and longitudinal gust alleviation ; then, the global fuel savings would be - 6.5 %.

A-3-3) RIDE CONTROL

Flight through turbulence, giving an uncomfortable ride, results both from :

- the rigid response of the airplane (usually the case for general-aviation with low wing-loading)
- and the excitation of the airplane's structural modes (usually the case for large flexible transport A/C).

Various active control systems have been successfully flight tested in both cases on experimental A/C (B-52/CCV, B-1 Bomber,...) and even certificated on transport A/C : on the B-747, a system was applied to improve the lateral ride qualities in the aft-fuselage, which operates the rudder to suppress the structural modes and to reduce the lateral acceleration (more than 50 % lateral acceleration reduction for the aft-cabin passengers). Since ride improvement systems are not flight critical, they should come very early into airline service, mainly on short-haul A/C flying often in a low altitude/bad weather ; but such comfort improvement has no direct pay-off on the energy efficiency.

A-3-4) GUST LOAD ALLEVIATION

The most spetacular application of a load alleviation and mode suppression system was made on the entire B-52-G fleet, in order to reduce the A/C acceleration response to turbulence at its primary bending mode frequencies, i.e. reducing fatigue damage during low altitude high speed penetration missions (increased service life by a factor of eleven !) [40 to 42].

Another application is the yaw damper installed on the Lockheed L-1011 to reduce vertical tail loads by about 20 %.

However a full application of gust load alleviation for structural weight savings is difficult because "flight critical" (very high system reliability is mandatory, and in some cases a gust alleviation system can induce more load than without ACT system).

A-3-5) FLUTTER MODE CONTROL

Since flutter phenomena is an explosive type of instability (i.e. can cause catastrophic structural damage in seconds), a flutter mode control system (typical "flight critical") would be applicable on transport configurations only for off-design conditions, such as "overspeed" [41].

However, flutter control systems are very attractive on some military A/C, for example to prevent wing/store flutter (the external load can be jettisoned in case of ACT system failure).

A-3-6) DIRECT LIFT AND SIDE FORCE CONTROL

Such capabilities must improve the maneuvrability of large transport A/C, mainly in terminal area ; thus, such systems will be helpful for improved take-off and approach trajectories (noise and delays reduction, increase of Airport Traffic, see section B-3). Direct lift can be developed by dedicated secondary flaps or by spoilers ; direct side-force can be induced by differential deflection of canard surfaces (figure 21 - a).

A-3-7) CENTER OF GRAVITY CONTROL

An appropriate transfer of fuel mass, through an automatic pumping system between various tanks is a very simple means of adjusting the A/C static margin to optimize its aerodynamic efficiency.

On a tailless configuration like Concorde-SST, this C.G control is vital to cope with the large rear shift of the aerodynamic center from subsonic to supersonic regime (see section A-7 and figure 43).

Even for a subsonic transport A/C, such a programmed C.G adjustment might be used to reduce the trim drag due to a too large static margin ; this technique is particularly attractive for long-range military A/C [8], like the bomber B-52 (2 % fuel savings), and the U.S.A.F airlift fleet : C-5A (- 1.6 % FS), C-141 (- 2 % FS), and

C-130 (- 0.9 % FS) ; on the civil transport side Lockheed estimates that 1 % aft C.G movement would lower fuel burn by 0.2 %, and about the same level is given for the Airbus A-300 (1 % fuel savings for 5 % aft C.G shift).

A-3-8) VARIABLE CAMBER CONTROL AND FLIGHT ENVELOPE LIMITING

The main objective of an automatic control of the wing flaps deflection is to optimize the aerodynamic efficiency L/D (fuel savings) during all flight regimes without pilot workload ; for each regime (take-off, climb, cruise, loiter, approach...) there are optimal combinations of leading-edge flap (or slat) and of trailing-edge flap deflections which give the best L/D; they are easy to control with the on-board computer.

For flight envelope-limiting, the active control system is used to prevent Aircraft from entering some dangerous portions of its flight envelope (in terms of angle of attack, normal acceleration, Mach number, etc...) ; safety is more involved than economy for such a task.

A-3-9) IMPACT OF ACTIVE CONTROL TECHNOLOGY ON TRANSPORT AIRCRAFT

To conclude on the ACT pay-off in performance and economy for transport A/C, it is important to recall that such a concept must be introduced and evaluated at the preliminary design stage of a project, taking into account the various interferences on the other disciplines (aerodynamics, structures, propulsion) ; in such a case, active control technology would have a decisive impact on the development of new projects over the next 20 years.

A good example of such impact was recently given by an USAF/FDL sponsored design exercise with Boeing [41] :
Two preliminary designs were conducted around a large tanker Aircraft project, able to off-load a 155 tons payload on a prescribed refueling mission (figure 24) ; the first design, using normal procedures, gave a very conventional configuration, with a gross weight of 450 tons ; the other project, in which five active control concepts were introduced simultaneously, was very different indeed :

- thanks to relaxed stabilities control on pitch and yaw modes, the horizontal tail was removed and the fin surface was reduced ; the wing size and weight were also reduced thanks to active load-control ; and the thrust of the four fan-engines was also reduced (less drag).

The main benefits due to ACT application are impressive :

- 25 % reduction on empty weight and 16 % on the gross weight,(G.W = 380 tons),

- about 25 % fuel savings

- a reduction of 20 % on the first cost for a fleet of 100 A/C,

- a reduction of 11.5 % on the yearly operating cost.

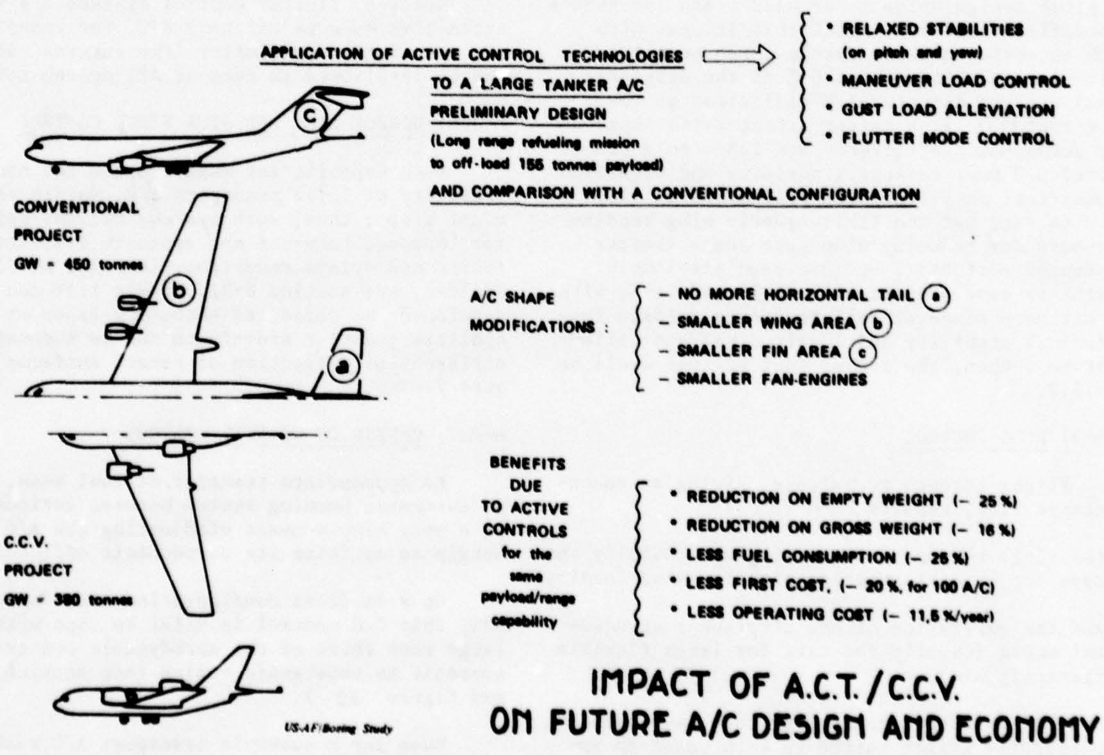


Fig. 24

A-4) PROGRESS ON AIRFRAME/ENGINE INTEGRATION

In this section, we shall review two ways for improving the propulsion system of some subsonic transport A/C, thankc to :

- a better design of the turbo-fan nacelle mounted on a wing,
- a new approach for an efficient use of a propeller up to high cruise speed ($M_\infty = 0.8$).

A-4-1) WING/NACELLES OPTIMIZATION

We have seen previously (section A-1-3,c) that a turbo-fan location at the wing-tip can reduce, by approximately one-third, the A/C induced drag ; but this tip location has several drawbacks (large yawing moment associated with tip-mounted engine failure, possible wing flutter problems, etc...)
But for wing mounted engine at intermediate spanwise locations, recent researches have shown that both underwing and above the wing nacelles/pylons locations can also lead to favorable interference effects.

A-4-1,a) Inboard - underwinged Engine installation

Some preliminary research at NASA-Langley [24] have been devoted to the elimination of adverse interference with poded engines ; in fact, it was demonstrated that it is possible to induce a favourable interference, which increases with lift : the reduction of the drag due to lift is due to a less outward spanwise flow below the wing (we have seen the same effect with a winglet at the tip) ; such favourable effect must be studied for each particular A/C configuration, taking into account the wing and nacelle shapes to design the specific shape of the pylon ; some theoretical approaches are now available for such optimization.

A-4-1,b) Over - the - wing nacelle

The upper-surface blowing (U.S.B) concept, where the fan-engine flow scrubs the wing upper-surface is well known by its convincing application on STOL A/C (Amstol Boeing YC-14, NASA/QSRA): very high lift is obtained by "supercirculation" effect generated by turning-jet effect around the deflected flap for take-off and landing ; this concept is also very attractive by its fly-over noise reduction for a given propulsion level ; but this scrubbing action at cruise speed produces both more friction drag and unfavorable transonic interferences [43].

An engine-nacelle location that is promising as a solution for avoiding this scrubing-effect is to locate the engine mounted relatively high and forward above the wing [44,24]; such a twin-jet A/C configuration was tested for the first time by V.F.W in Germany [45] and typical results are shown on figure 25a; these lift and drag variations with the jet velocity ratio are relative to the wing and fuselage only, (the propulsive nacelles being non-metric); the velocity ratio $V_j/V_\infty = 4.4$ is representative of turbo-fan engine - FPR = 1.6 - operation at the start of climb : the jet exhaust induces a significant increase of lift and gives a reduction in drag due to lift which leads to a 6 % increase in lift/drag ratio in climb condition ; at take-off and landing conditions, with flap-down this entrainment effect induces a larger CL increment; this induced "supercirculation" effect would be even larger by deflecting the jet onto the flap-down, as proposed by NASA-Langley [44].

In cruise condition, the velocity ratio is much smaller (~ 1.6 at M = 0.7) and, these gains on CL and CD are much smaller (about 3 % on total CD). Theoretical approach of this concept has been already developed by NASA and Boeing [44,24] which can help the optimization of each particular configuration ; this includes the design of satisfactory contoured nacelles and pylons ; transonic tests made by Boeing have shown that installation of symetric nacelles and pylons caused a large reduction of the drag divergence Mach number and a drag increase at cruise lift (figure 25b) ; on the contrary, the configuration with contoured nacelles and pylons shows a better limit Mach number that the wing-body alone, and even no extra-drag at transonic speeds.

All these results are very encouraging and must be further studied because such concept can open the way to very attractive transport A/C configurations, taking advantage of the shielding effect of the wing to reduce the fly-over noise level and of the jet-flap effect to reduce take-off and landing distances ; finally, this over-the-wing location of the propulsive nacelles permits low-wing configurations with large turbo-fans without ground clearance problems as on conventional underwinged installation (see the "span-loader" concept in section A-5).

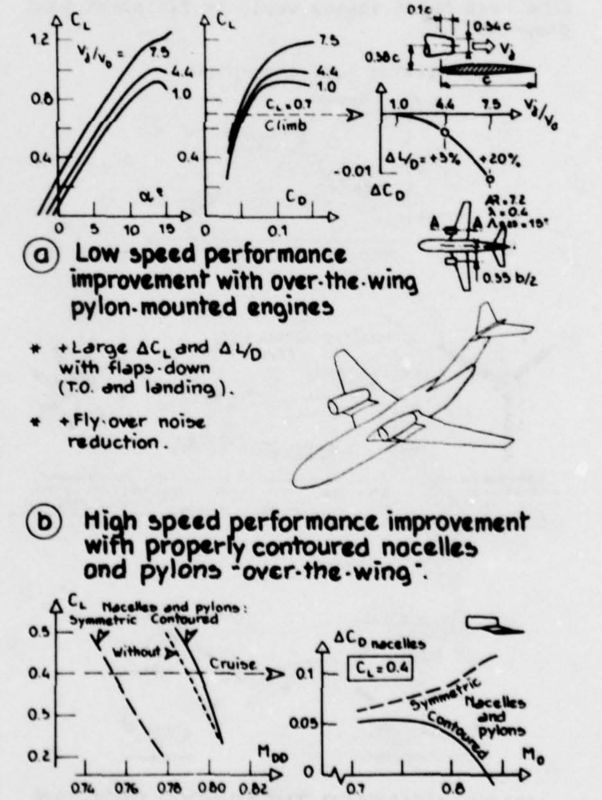


Fig. 25

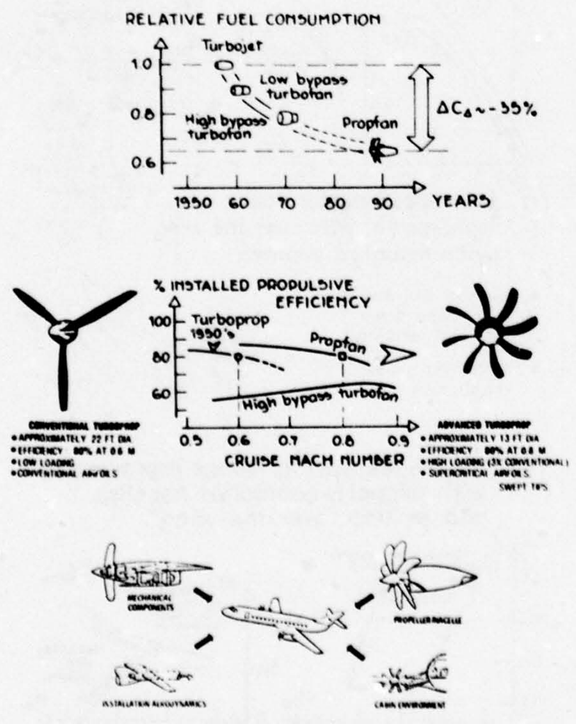
A-4-2 TRANSONIC PROPELLERS FOR FUEL ECONOMY

In the past, propellers were used very efficiently at cruise speeds up to about Mach 0.60 ; above this speed, the efficiency falls rapidly due to increased transonic drag on the blades ;

to overcome this drag divergence at higher cruise Mach number, there are two well known solutions : using thinner and/or supercritical blade sections and sweeping the blade leading-edge ; and now, with the use of composite materials and advanced constructions techniques, it is possible to build such blades [46, 47].

As a part of its Aircraft Energy Efficiency programm [1], NASA has asked the Hamilton Standard division of United Technologies to design and test in wind-tunnel a family of transonic propellers, or "prop-fans" ; these tests have shown that a full-scale propulsive efficiency of about 80 % can be obtained at a cruise Mach number of 0.8, i.e. about 20 % higher than that of the best advanced Turbo-fan (fig.26) ; such a propeller requires a power loading about three times higher than that of conventionnal propellers (i.e. about 300KW/m2) with eight blades, having very thin (2 %) and swept (30°) tip sections, and advanced supercritical airfoils all along the blade ; finally the prop-fan diameter is about one-half that of a conventional propeller (no installation problems with a low-wing configuration).

The above mentioned gain on propulsive efficiency over the conventionnal turbo-fan comes mainly from much lower momentum losses with the lower pressure ratio of the prop-fan, but also from the elimination of the turbo-fan shroud drag ; the gains are even better at low-speed/off-design conditions thanks to its variable pitch, leading to shorter field lengths and better rate of climb (the best final saving would be for short-haul prop-fan A/C).



NASA ADVANCED TURBO-PROP PROGRAM

Fig. 26

However, the integration of the prop-fans to the airframe (figure 26) is still quite critical, due mainly to the interaction between propeller slipstream and the wing in a transonic environment (supervelocities, plus flow rotation,) but also between the propeller itself and the spinner/nacelle arrangement ; both analytical and experimental research are still needed to optimize a complete A/C configurations. Another critical area is the fuselage, located in the noise field of the transonic propeller (propeller tip speed = 240 m/sec, i.e. slightly supersonic at M = 0.8 cruise), which gives an overall near-field sound-pressure level of about 146 dB ; then, a very effective acoustic treatment of the fuselage around the wing-mounted prop-fan is mandatory (very difficult to cure because this noise is mainly at low frequency, which needs a quite large structural weight penalty, i.e. some degradation in the fuel efficiency).

Finally, the mechanical maintenance costs must be much lower than with the old turbo-prop A/C (mainly on the gas-turbine, on its gearbox and on the prop-fan itself) ; but, again, advanced technology can be applied (better modularity, increased mean-time between failure).

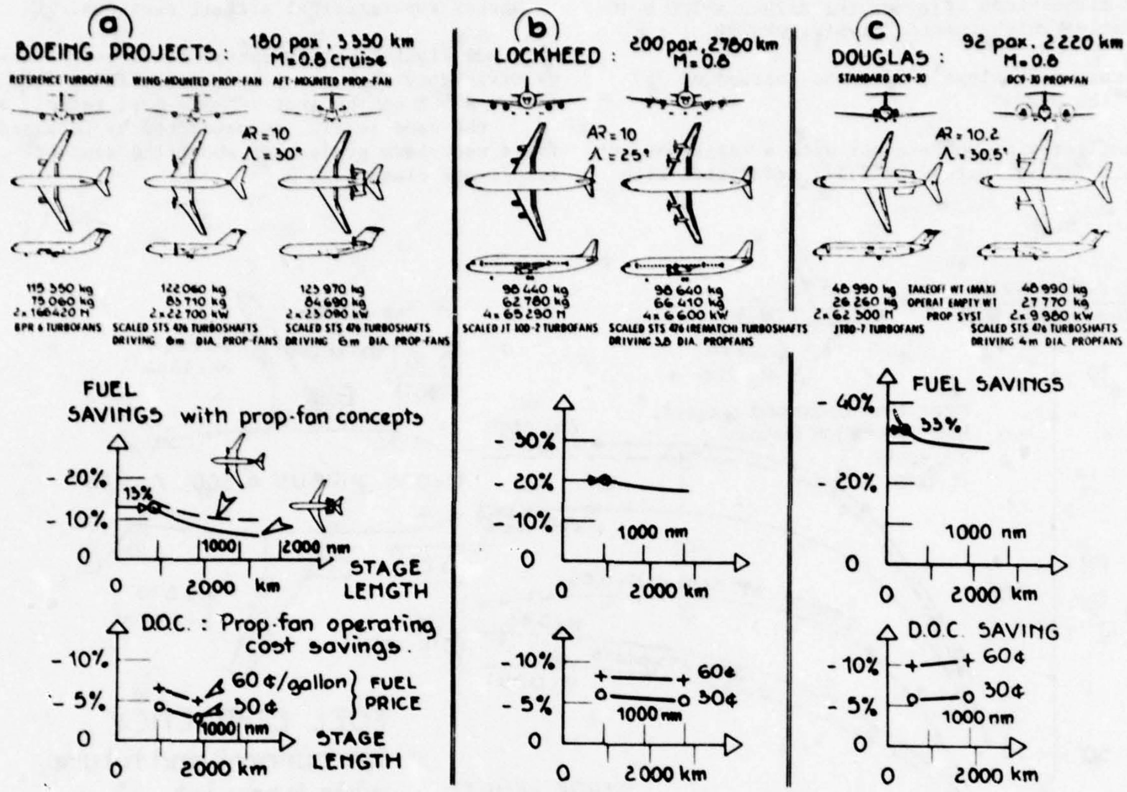
To evaluate the future of new propeller-driven Transport A/C, it is interesting to analyse the results of preliminary design projects made by three U.S. airframe manufacturers for NASA [47] to point out the fuel and operating costs savings potential when compared with conventionnal Turbo-fan A/C (figure27) ; for all these studies, the ground rule was a cruise Mach number 0.8 and the use of a prop-fan family already developped by Hamilton Standard from their transonic wind-tunnel tests :

a) In the Boeing design study (figure 27a), two prop-fan powered transport configurations were compared with an equivalent technology level turbo-fan configuration, having the same mission (180 pax, on 3300Km at M = 0.8) : all three configurations are twin-engine/wide-body A/C, using 1976 airframe and 1980 engine technologies [48]. One pro-fan design has the engines mounted on the wing, the other on struts at the fuselage after-body ; both designs have higher empty weights than the turbo-fan configuration, due to the extra-weight of prop-fan systems, but also to the weight penalty for cabin noise suppression (2670 Kg) with the wing-mounted prop-fans ; the aft-body prop-fan was studied to avoid this penalty but, in this case additionnal structure is required for engine struts, and larger tails, and to cope with more severe acoustic fatigue due to the propeller/fuselage proximity.

The fuel savings for a 500 n.M stage length is around 13 % for both configurations, and direct operating cost savings are between 4 and 6 %, depending upon the fuel price.

b) The Lockeed-California study [49] is based on four engines configurations for 200 passengers on maximum range of 2780 Km at M = 0.8, with a 1985 service introduction taking account of new technologies (supercritical wing, AR = 10, active controls for relaxed stability, composite secondary structure and advanced engines) ; figure 27b shows that the gross-weights of the two candidates are about equal (compensation between less fuel and more structural weights for the prop-fan solution). The fuel savings for the prop-fan concept is about 20 % for a typical 475 n.M stage length with 58 % load factor. (The specific fuel consumption is reduced by 19 % at cruise and by 26 % during climb, the later figure beeing very attractive for short-haul missions).

The D.O.C. savings are between 6 and 8.5 % depending upon the fuel price.



NASA PRELIMINARY DESIGNS OF PROP-FANS TRANSPORT A/C

Fig. 27

c) In the Douglas study[50], the DC-9-30 was used as a basis of comparison with a modified version equipped with two wing-mounted prop-fans: here, the gross take-off weight and payload (92 pax) were held constant ; on the propeller-driven version the wing was moved forward and the vertical tail was increased by 30 % (for one engine-out control) ; again the prop-fan empty-weight is a little larger than that for the turbo-fan configuration. The fuel savings for the prop-fan concept are much larger than those of the two previous studies because the reference A/C DC-9-30 uses old low BPR/JT 8-D turbo-fans ; on the other hand, the prop-fan design was based on advanced core engine technology (JT-10-D) and on a 8 bladed propelled with 244 m/s. tip-speed, giving a propeller efficiency of 0.8 and installed T.S.F.C of 0.6 Kg/h/daN (0.53 lb/lb/hr) ; in these conditions, the prop-fan derivative uses 33 % less fuel than the DC-9-30 for the 290n.M stage length ; and for the same T.O. weight, its range is increased by 73 %.(figure 27c)

The D.O.C. savings for a higher TSFC (0.65 lb/lb/hr) are still between 5.5 and 10 %, depending upon the fuel price.

To conclude on the future of the pro-fan, it is fair to say that this concept is again attractive, not only for its large fuel savings potential, but also by its propulsive efficiency superiority over the turbo-fan at off-design regimes, i.e. take-off and climb, cruise at lower altitude and Mach number (very interesting for civil short-haul and military Cargo A/C).

More research+developpment are still necessary , including demonstrator A/C, to solve various technical problems (transonic propeller fly-over noise and cabin noise/vibration level, airframe/engine integration, mechanical turbo-prop maintenance).

A-5) FUTURE APPLICATIONS OF NEW TECHNOLOGIES TO SUBSONIC TRANSPORT A/C

A-5-1) SOME NEAR-TERM FUEL EFFICIENT SUBSONIC TRANSPORT CONFIGURATIONS

We have seen, in the previous sections, various attractive means of fuel savings in a short term period by minor Aircraft modifications and improvements (on aerodynamics, structures, and propulsion system) ; but, in some cases, such modifications are not cost/effective for the operator : for example, although the fuel savings with a reengined Aircraft is very substantial (i.e. new CFM-56 on a old B-707, see figure 32), the cost of the engines and the airframe modifications could have such impact on D.O.C increase that negates this type of fuel savings option ; on the contrary, a more modest energy saving given by an aerodynamic improvement (i.e. wing-tip extension, etc...) is cost/effective due to its very small negative impact on the D.O.C.

A second way which offers greater potential fuel savings is the development of derivative Aircraft to increase the payload/range characteristics of the basic design. Such operation generaly requires a substantial development effort ; for example fuselage stretch, introduction of composite secondary structure, general drag reduction program, and even, a complete redesign of the wing : this last option was taken recent-

ly by Airbus-Industrie for the Airbus A-300 B-10 derivative which incorporates (figure 28) :

- a shorter fuselage (232 seats instead of 269 for the B-2/4)

- a smaller wing surface but with a larger aspect ratio (10.16 instead of 8.57), and fitted with thicker supercritical airfoil sections.

This new lighter configuration has a better energy efficiency than the previous configuration (about + 6 % on the seat x Km/Kg fuel ratio), and the same level as predicted by Lockheed for a near-term project of about the same payload/range class [26].

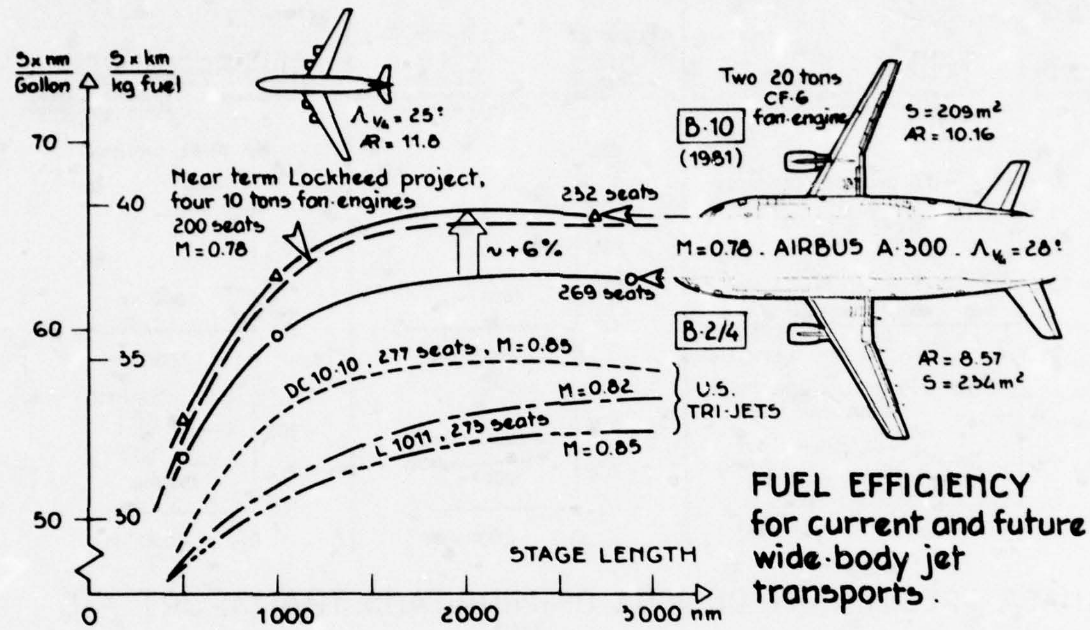


Fig. 28

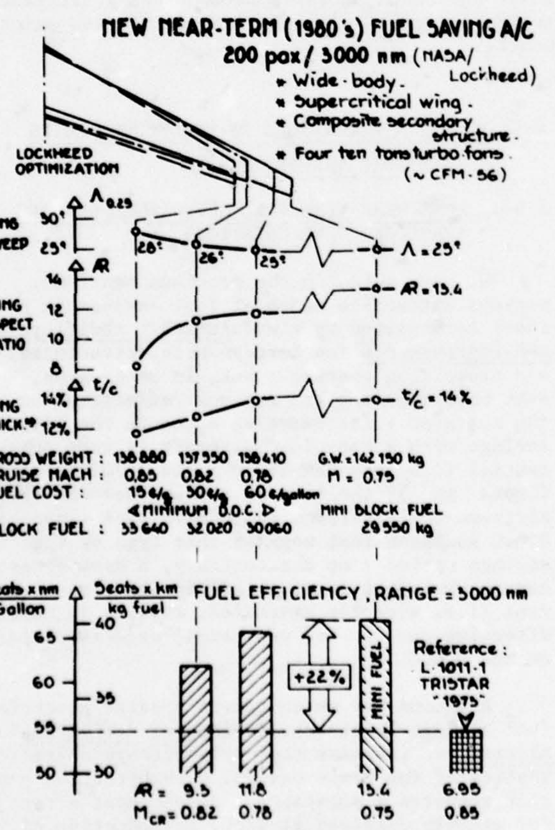
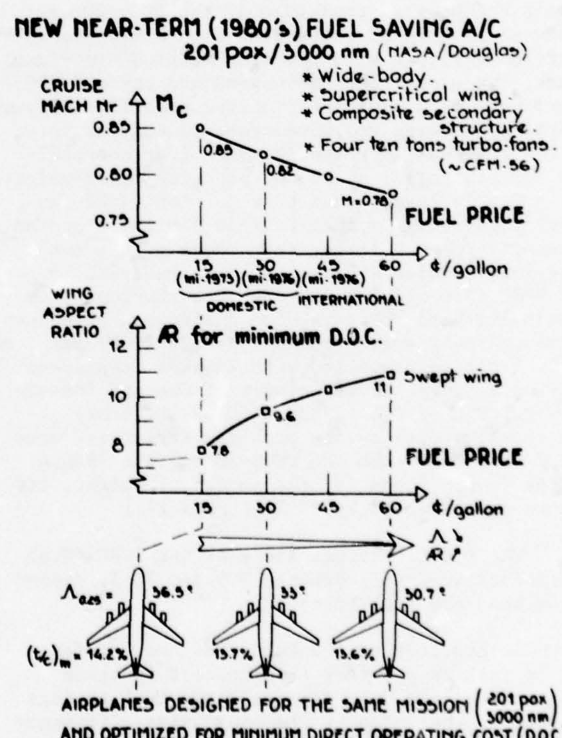


Fig. 29



GROSS WEIGHT	126 750	124 890	122 990 kg	G.W. ↘
FUEL WEIGHT	31 570	29 540	27 630 kg	F.W. ↘
FUEL SAVED	0	-6.5 %	-12.5 %	

Fig. 30

This Lockheed configuration is a part of a NASA parametric study (RECAT program) around a third way for fuel savings : the development of new near-term Aircraft, using 1980' level of technology in all areas :

- aerodynamics (supercritical wing with optimized geometry),

- advanced propulsion,

- advanced structure (new metallic structural concepts and composite secondary structures),

- active controls.

The main objective of this program was to analyse the impact of the fuel price (15,30 and 60 ¢ /gallon) on a new Aircraft configuration, optimized either for the minimum D.O.C or for the minimum block-fuel on a given mission (200 pax on a 3000 nM stage length).

The major trends of the Lockheed [26] and Douglas [30] studies are given on figures 29 and 30 , respectively ; the major impacts of fuel cost escalation are :

- a reduction of cruise Mach number,

- an increase of the wing aspect-ratio,

- a decrease of the wing-sweep,

- an increase of the supercritical wing thickness.

All these trends are accentuated when the airplane is optimized for minimum block-fuel instead of minimum D.O.C ; in the case of the Douglas study for example, optimization to minimum block-fuel leads to an unswept wing of very large aspect-ratio : AR = 15.5 (not shown on the figure 30) ; this configuration needs a little smaller block-fuel (26.340 Kg),but has a larger gross-weight (124260 Kg) than the previous minimum D.O.C/60 ¢ project ; but more pertubing is a too low cruise Mach number : M = 0.70 only, and a too large span (b = 56.9 m)for the existing Airports handling capacity. The same trends are confirmed by the Lockheed optimization to minimum block-fuel (figure 29).

It is important to point out that, generally, a configuration optimized for fuel savings is not the most economic one for the operator, because its larger empty weight (more manufacturing cost) and its smaller productivity (lower cruise speed) ; this statement appears clearly in a SNIAS study [51] on a medium-range twin-turbofan transport optimization ; furthermore, the same conclusions are shown by Boeing from a parametric design study of large advanced military transport [52] ; using modern computing techniques with ten independant variables, the main objective was to optimize a cargo A/C project alternately for minimum gross weight and for minimum block fuel on a prescribed mission :

- fixed payload : 181 tons

- fixed range : 5500 nM

- T.O field length : 8000 ft (2450 m)

- cruise speed : M ≅ 0.78

Finally the technology level (on aerodynamics, structures, propulsion and active control systems) was taken appropriate to a 1985 delivery.

The table on figure 31 shows that two opposite requirements give very different configurations ; the "minimum fuel" project has :

- a larger gross weight,

- a larger wing surface,with a much larger aspect-ratio (AR = 12 instead of 8 for the "minimum weight" project)

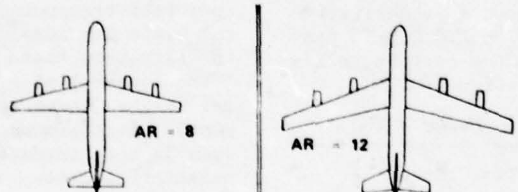
- and a 14 % reduction on the mission fuel weight.

MILITARY CARGO A/C PARAMETRIC STUDY

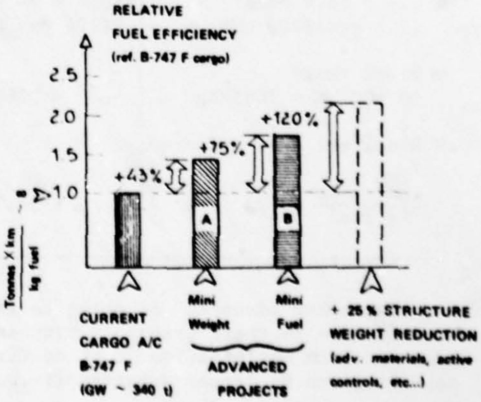
- RANGE : 5500 nm (10000 km)
- FIXED PAYLOAD : 181 tonnes
- T.O. FIELD LENGTH 8000 ft (2400 m)
- CRUISE MACH ~ 0.78

A — MINIMUM WEIGHT PROJECT

B — MINIMUM FUEL PROJECT



	A		B
TAKE-OFF GROSS-WEIGHT	GW	= 724 t	770 t
MISSION FUEL	W_F	= 258 t	221 t
1985's ADVANCED TURBO-FANS	T	= 4 × 42 t	4 × 39 t
WING-LOADING	GW/S	= 755 kg/m²	609 kg/m²
THRUST/WEIGHT	T/GW	= 0.23	0.20
WING SPAN	b	= 88 m	123 m
ASPECT-RATIO	AR	= 8	12
WING SWEEP	$\Lambda_{c/4}$	= 10.9°	17.9°
MEAN THICKNESS	t/c	= 10 %	10 %



Boeing study, 1976

Fig. 31

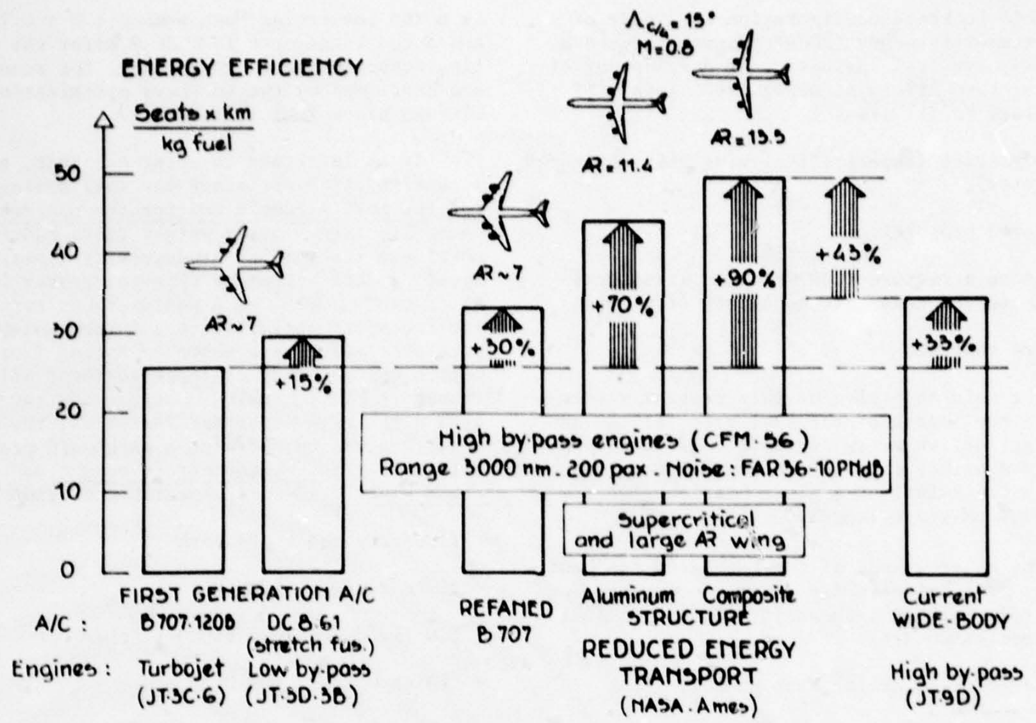


Fig. 32

Both projects are much more fuel-efficient than a current B-747 freighter (+ 43 % and + 75 % for mini-weight and mini-fuel, respectively) ; reducing by 25 % the structure weight fraction (thanks to far-term advanced technology) gives a cumulative gain of about + 120 % !

To conclude on the potential gains on fuel consumption during the next two decades or so, the figure 32 gives a last picture of a possible evolution of a subsonic transport refered to the first generation/turbo-jet A/C (B-707 or DC-8) : the introduction of new high-by-pass-ratio turbo-fans (CFM-56, JT-10D, etc...) will give the possibility of about 30 % more energy efficiency...and much less noise !

A slightly larger gain in energy efficiency was calculated by Dassault/Breguet on a derivative of their Mercure equipped with TWO CFM-56 fan-engines, when compared with the current B-727-200, on a typical 600 nM mission [88]:

B-727-200	Mercure 200
* Three JT 8D-15 (3 x 15500 lb)	* Two CFM-56 (2 x 2500 lb)
* G.W = 86.4 tons (153 pax/2100 nM)	* G.W = 76 tons (174 pax/2300 nM)
* Block fuel on 600 nM = 7065 Kg	= 5266 Kg
* Resultant fuel efficiency :	
$\frac{\text{seat x Km}}{\text{Kg fuel}}$ = 24	= 36.7 (+ 52 %)

The other advanced technologies introduced by NASA/Ames in their transport synthesis computer program optimization [53] confirm the pay-off given by larger aspect-ratio wings fitted with supercritical airfoils and by the introduction of a graphite/epoxy wing structure.

A-5-2) LARGE UNCONVENTIONAL CARGO A/C

Almost all the new technologies discussed previously can be applied to a very attractive concept, the "spanloader" A/C, (figure 33) for a future worldwide air-freight transportation system ; both the military and the Airlines would derive cost savings from joint development of such a cargo system, in the 1990's [5,54].

The basic requirement, for an efficient air cargo system, is to be able to carry the standard intermodal container (8' x 8' x 20') currently transported by trucks and ships ; the basic new idea (due to NASA scientists) is to distribute these containers along the span ("spanloader") of a huge wing to save structural weight (large reduction of the bending-moment) ; furthermore, a constant chord along the span is very favourable to reduce the wing manufacturing cost.

We have seen that the supercritical technology is the way to efficient very thick airfoil (17 % to about 22 % or more) and their shape is well suited to accommodate two rows of such containers.

But landing loads will have to be distributed over the span as well, and another good idea is to use an air-cushion landing system [37]; the air-cushion technology has been already flight tested on a C-8 "Buffalo" (USAF "A.C.L.S" program) and this concept allows to operate from unprepared terrain and water, a very attractive capability for a worldwide transport system.

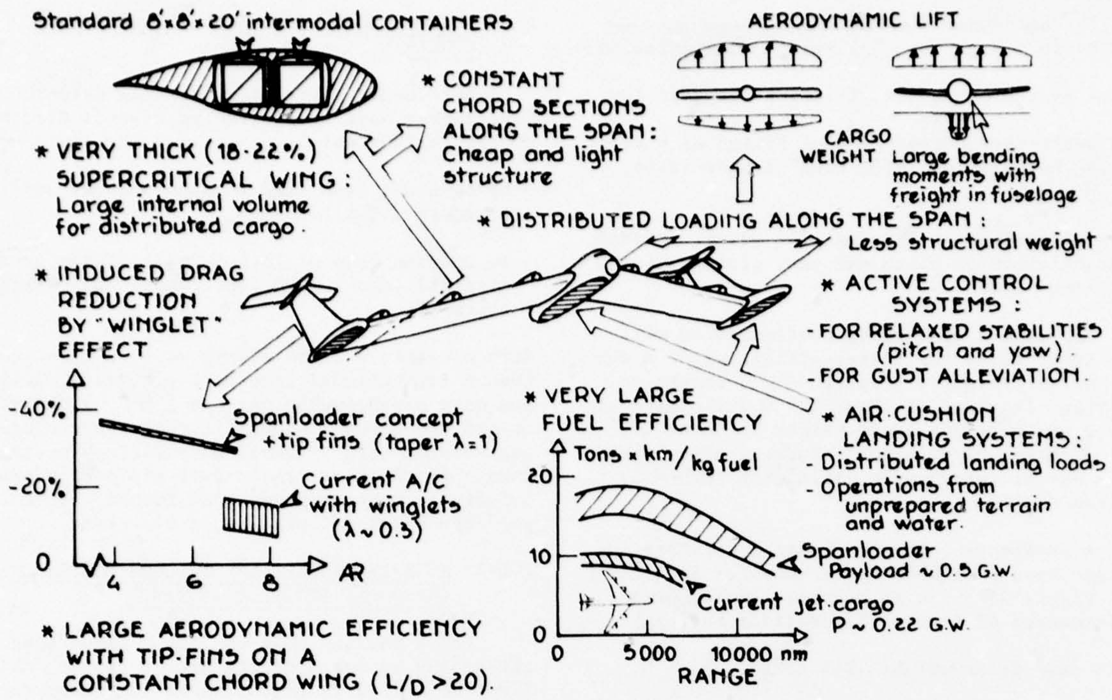
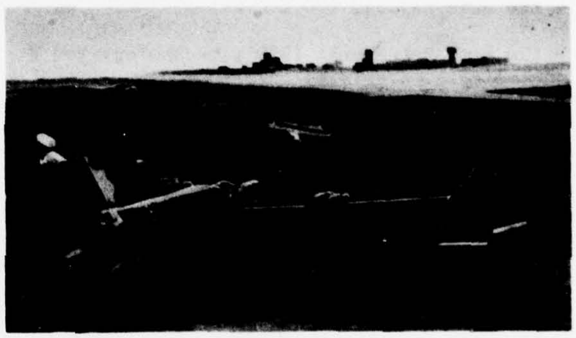


Fig. 33



Ref. NASA

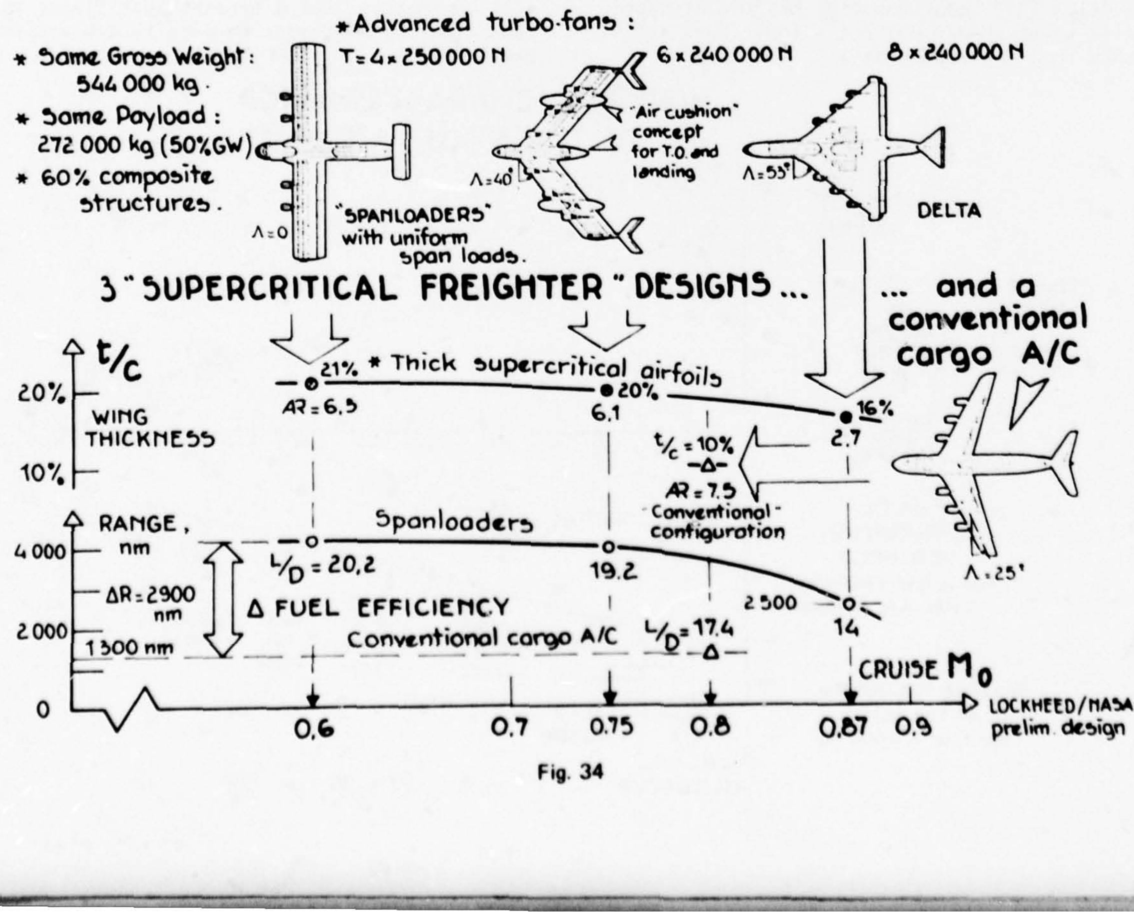


Fig. 34

The aerodynamic efficiency of such concept will be very high for "all-wing" configuration:

a) the wetted area, i.e. friction drag, is low,

b) a swept-back untapered wing fitted with tip-fins has a large "effective" aspect-ratio, [55],

c) an active control system will permit relaxed stabilities on pitch and yaw, giving a large trimmed L/D.

Finally, a"spanloader"configuration will have about twice the energy efficiency of a current B-747 freighter (figure 33) thanks to a payload fraction of about 0.5 G.W (instead of 0.22), an operating empty-weight of about 0.23 G.W. (instead of 0.45 for a current Air-cargo), and a better aerodynamic efficiency (L/D $\cong$ 22 instead of 17)

A parametric study of large freighters designs have been made by Lockheed for NASA [56]. Figure 34 gives an overview of the main performances of four configurations having :

- the same gross-weight (544 tons),

- the same payload (50 % G.W.)

- the same structural 1990's technology (60 % composite materials)

- and 1990's advanced turbo-fans.

A conventional cargo A/C configuration was calculated as a reference, which have a current cruise Mach number (M = 0.80) but a very poor range (R = 1300 nM) ; at the opposite, two"spanloader" configurations have about the same attractive range (R $\sim$ 4000 nM), but swept configuration (40°, AR = 6.1) has a higher cruise speed (M = 0.75) than the straight wing configuration (M = 0.6), i.e. a much better productivity ; finally, the delta (53°) configuration has the highest cruise speed (M = 0.87) but a lower fuel efficiency than the spanloaders.

A-6) TOWARDS MORE ECONOMICAL VTOL AND STOL CONCEPTS

For twenty years, considerable Research and Development have been directed towards Aircraft configurations able :

- to take-off from, and to land on, very small platform (VTOL concept),

- to operate from or into a small unpreapared airfield, about 2000 foot length or less (STOL concept).

Both concepts will be always more fuel consuming than a conventional transport Aircraft (CTOL) and more expensive to operate [57]; but their unique operational flexibility is increasingly appreciated both by civil and military operators ; furthermore, their fuel efficiency can be relatively more improved than future "conventional" transport A/C previously discussed.

A-6-1) HOVERING CAPABILITY THROUGH ROTOR CONCEPTS AND FUTURE ROTORCRAFT

For a machine able to lift a given load off the ground by means of its engine thrust, the first objective is to calculate the power required, to estimate the price to pay ; the basic equations of the mechanics indicate that from a hovering efficiency standpoint, it is advantageous to accelerate slowly a large mass of air, as it is the case for a helicopter rotor T/P = 2/Vs,(Vs being the slipstream velocity behind the actutor,requiring a power P to develop a thrust T) ; for a high speed-jet exhausting from a turbo-jet engine or from a rocket, Vs is about 600 and 2500 m/sec. respectively, instead of Vs $\sim$ 25 m/sec. for a helicopter rotor ; this explains the very large fuel consumption during the hover phase of a jet-VTOL or a space-launcher ; figure 35 gives an overview of the thrust/power ratio of various VTOL candidates as a function of the disc-loading, and also the fuel consumption for a hypothetical 5 tons VTOL (one order of magnitude between rotors and rocket).

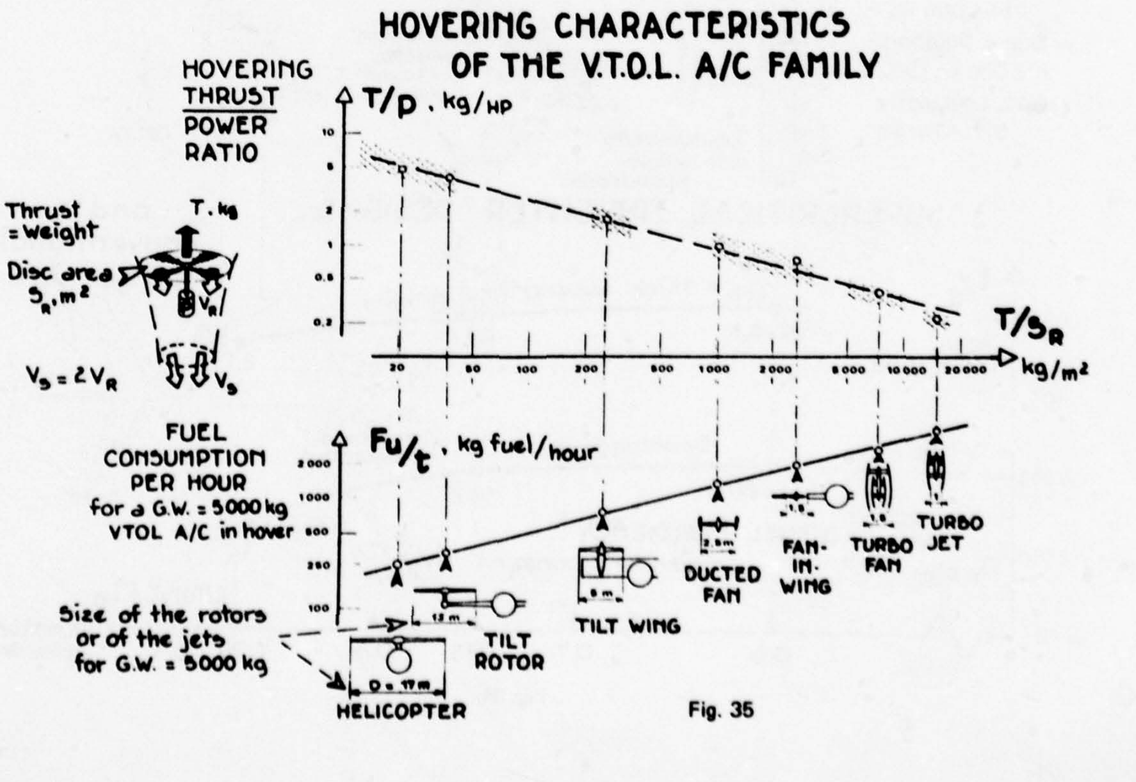


Fig. 35

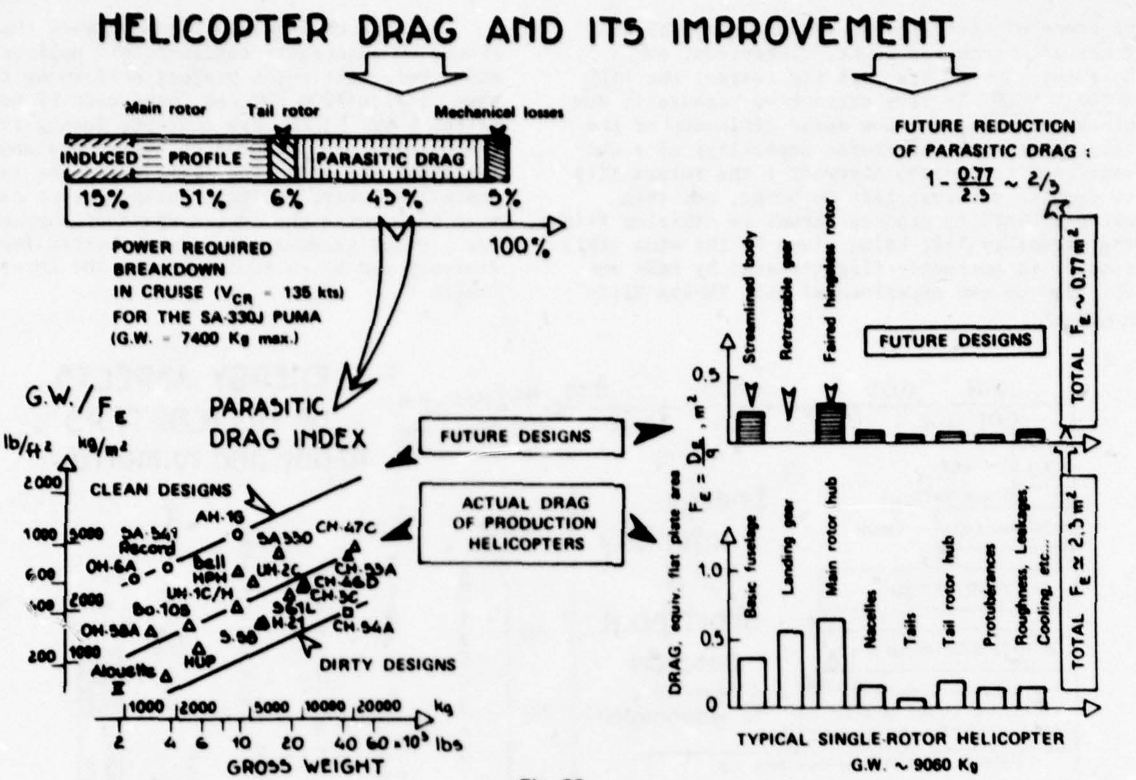


Fig. 36

For some military applications, the hovering time can be very short and the transition to high speed cruise regime takes less than one minute : in such cases turbo-fan engines are well adapted, as demonstrated by the VTOL Combat A/C "Harrier" (the only concept that reached a large development).

But when a long hovering time is mandatory (rescue, etc...) and a high noise level prohibited (inter-city service, etc...), the best concept is the rotorcraft because its good hovering efficiency and its low slipstream velocity (low noise, low ground erosion, etc...) ; the major drawbacks of conventional helicopters were their poor cruise speed, their maintenance problems and their high level of vibrations ; but since few years, the manufacturers and Research laboratories have considerably improved the helicopter performances thanks to a large drag reduction [58, 59 and 60] ; figure 36 shows that the parasitic drag still takes more than 40 % of the power required at cruise conditions for a recent helicopter (SA 330 "Puma", [58]), but much more for previous "dirty" designs ; in fact, large gains are still possible on future designs.

As for the future conventional airplanes, the potential energy savings also depend upon other technologies improvements (Rotor Aerodynamics efficiency, structural weight reduction via composite materials, improved gas-turbine SFC, etc...) ; thus, figure 37-b illustrates the main conclusions from a NASA/Vertol study based on a 100 passengers transport helicopter design [60] using some advanced technologies available in the 1990's :

- regenerative-turbine engines, giving SFC as low as 0.35 lb/hp/hr,

- rotor cruise efficiency improvement, $\Delta\left(\frac{L}{D_E}\right)$=+20%, through the reduction of profile power,

- rotor hover efficiency improvement (figure of Merit up to 0.82), through about 10 % reduction of the induced power,

- advanced structures, giving about 12 % empty weight savings, through an extensive use of composite materials.

Combined effects of these improvements could save up to 38 % of fuel when compared to current helicopters still in operation ; the same figure 37-b shows that "super-emergency" power engines, giving 200 % power to satisfy hover "one-engine-inoperative", would allow installation of two instead of three engines on this project, with 10 % G.W savings and about 25 % fuel economy.

Now, it is interesting to estimate the energy efficiency of current and future helicopters as compared with other Air and Ground Transportation systems, on the same short-haul mission (i.e. 200 nM, like New-York to Washington) ; these comparisons, calaculated by W.Z. Stepnewski [61], are given on figure 37-a, in Kg fuel/passenger x Km (or gallon/pax x nM); taking into account realistic load factors for each mode of transportation : it is clear that current helicopter still in service on New-York Airways (Sikorski S-61-L, 28 seats, with 60 % load factor) uses much more energy per passenger than bus, train or standard automobile. But, more interesting is a 1985's advanced technology 100 passengers helicopter, the TH-100, studied by Vertol/Boeing [62], which gives about 32 % fuel savings as compared with the S-61, and becomes competitive with regular jet or prop A/C service (with certainly less delays) ; the longer term helicopter projects previously described on figure 37-b are even more fuel efficient.

By definition, the cruise speed of a conventional helicopter is limited by the development

of transonic troubles appearing on the blades (increased required power, vibrations, etc...), to about 130-170 Kts ; to fly faster, the TILT ROTOR CONCEPT is very attractive because it combines the hover and low speed efficency of the helicopter with the cruise capability of a conventional turbo-prop Aircraft : the rotors tilt to provide vertical lift in hover, and then swing forward to produce thrust in cruising flight, the necessary lift being given by the wing :this concept is currently flight-tested by NASA and US. Army on two experimental Bell XV-15A Tilt-rotor A/C.

An interesting comparison between the previous 100 passengers tandem-rotor helicopter and a twin-tilt-rotor project performing the same mission (200 nM) has been made by Boeing-Vertol [62]; the two concepts (using 1980's technology) are pictured on figure 38 a and b : for about the same gross-weight and the same installed power, the tilt-rotor concept has more than twice the cruise speed of the helicopter , which translatesin a much better fuel efficiency and block-time for this 200 nM stage length :

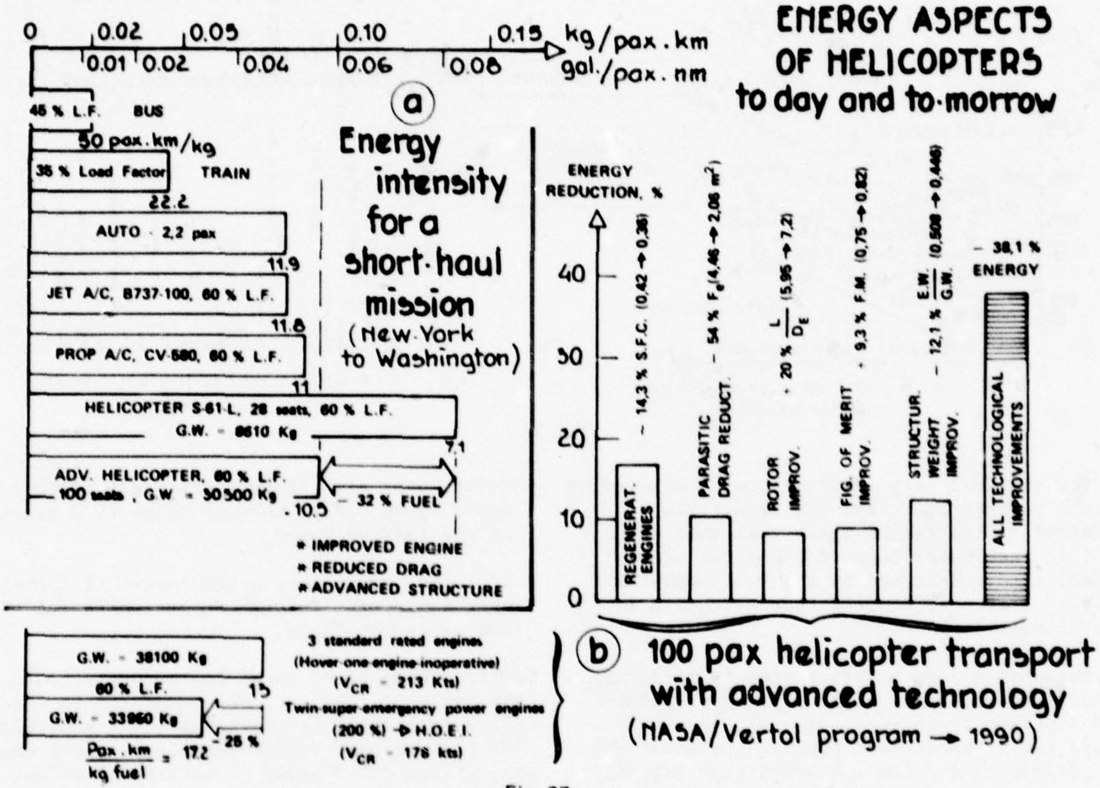


Fig. 37

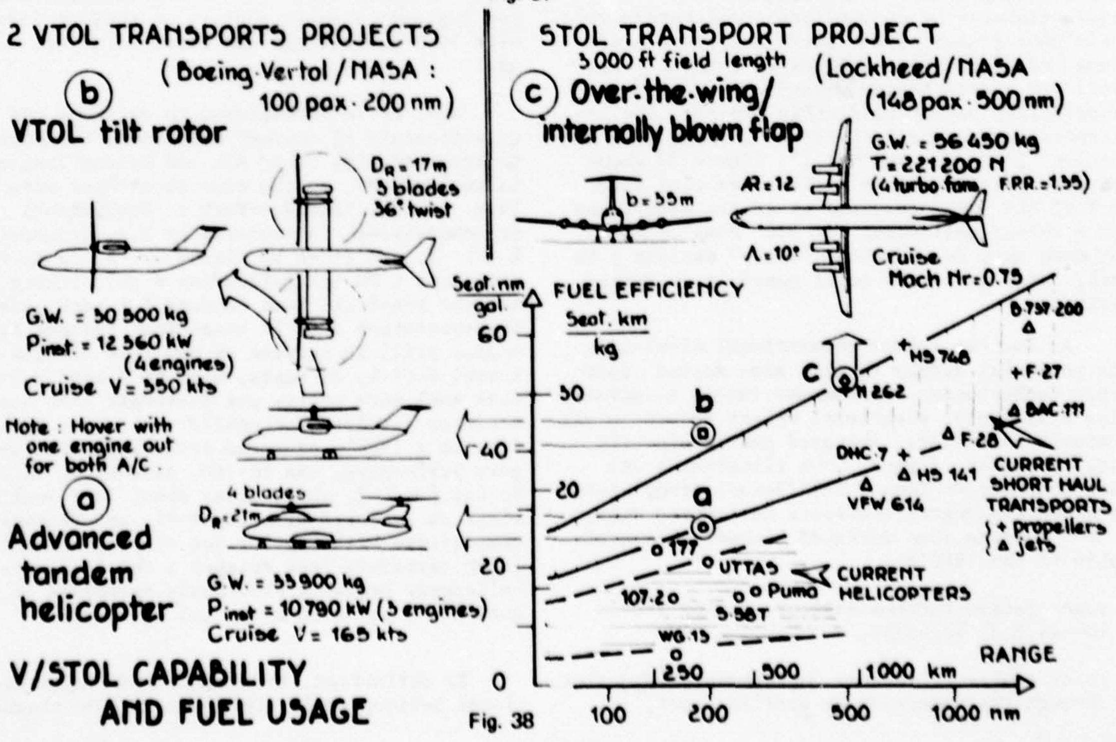


Fig. 38

Mission : 100 pax/200 nM	V cruise Kts	Block time,min	seat x Km / Kg fuel
(a)helicopter A/C	165	80	16
(b)tilt-rotor A/C	350	45	26
	+ 110 %	- 44 %	+ 60 %

the fuel efficiency versus range, on figure 38 , demonstrates other important trends :

- the advanced large transport helicopter shows a marked improvement over the best current helicopters in service,

- the tilt-rotor transport concept is above the winged-vehicle band for such short stage lengths.

Finally, the perceived-noise levels at 500 ft sideline in hover are quite low (92 and 98 PndB respectively for the helicopter and the tilt-rotor), the later being quieter in cruise mode.

To conclude on the Rotorcraft configurations, it seems they have a bright future for passengers and freight transportation when vertical flight is mandatory ; the most demanding VTOL capability is now for offshore oil platform traffic (North Sea, Gulf of Mexico,etc..), where sufficent range and speed are needed ; also good navigation/equipments and de-icing, and easy maintenance are mandatory for such all-weather missions.

A-6-2) SHORT TAKE-OFF AND LANDING CONCEPTS

We have already seen that short-field length for take-off and landing are obtained through high lift systems and/or low wing loading ; these high lift performances can be obtained either with sophisticated mechanical flaps or with "powered lift" using the deflected slipstream of propellers or turbo-fans (jet-flap effect) ; all these concepts are now well proven and operational ; but, here again, the question is "what price to pay for STOL performances ?", or, more precisely, the amount of mission fuel as a function of the field length ?

A parametric study has been made by Lockheed for NASA [63] on the design of a short-haul A/C for fuel conservation ; a typical mission : 148 pax on 500 nM stage length was taken with the same level of technology (advanced NASA QCSEE fan-engine project with FPR = 1.35, i.e. very low noise ; high aspect-ratio wing with supercritical sections, etc...) ; two concepts have been compared for the same optimum cruise Mach number $M_0 = 0.75$:

- a four turbo-fan-over-the-wing scheme with internally blown flap (OTW/IBF), AR =12, $\Lambda = 10°$, (this concept is currently flight-tested by NASA on the experimental QSRA/Boeing A/C),

- a more conventional twin-turbo-fan A/C with sophisticated mechanical flaps on a wing of AR = 10, $\Lambda = 10°$; the figure 39 shows that the best choice for STOL performances (2000-3000 ft) is the four over-the-wing-engines A/C ; if longer runway is available (3000-4000 ft) the RTOL fan-engines A/C with conventional flaps is more energy efficient. For the same 3000 ft field length, they have about the same direct operating cost but the fuel consumption is much lower for the OTW/STOL concept.

THE PRICE TO PAY FOR SHORT TAKE-OFF/LANDING

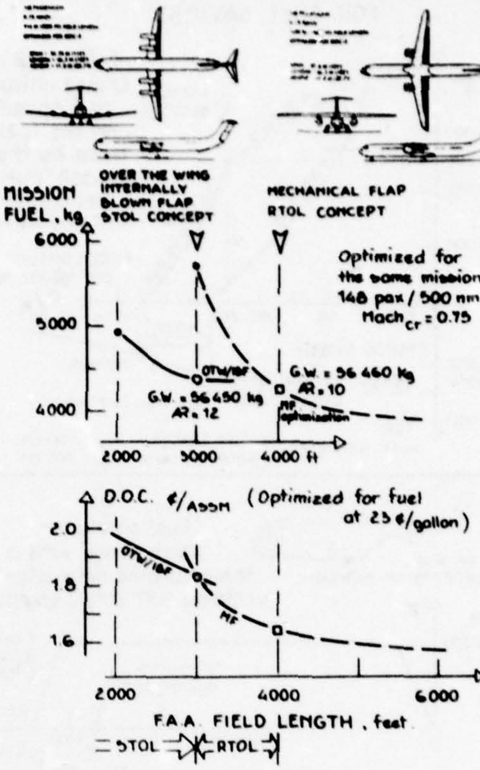


Fig. 39

Finally, both concepts have about the same gross-weight (≈ 56.5 tons) and the same thrust/weight ratio (≈ 0.4).

The fuel efficiency of the OTW/IBF concept for 3000 ft field length = 31.15 $\frac{\text{seat x Km}}{\text{Kg fuel}}$ has been plotted on figure 38c to show that such STOL transport A/C has about the same energy efficiency than the best current short-haul A/C, but with much better field performances (half runway length, less noise).

To conclude this section, figure 40 gives two aspects of operational procedures (see section B-2) used on helicopters to reduce the fuel consumption :

- optimal cruise speed and altitude for fuel savings,

- cruise on two-turbines for a 3-turbines configuration.

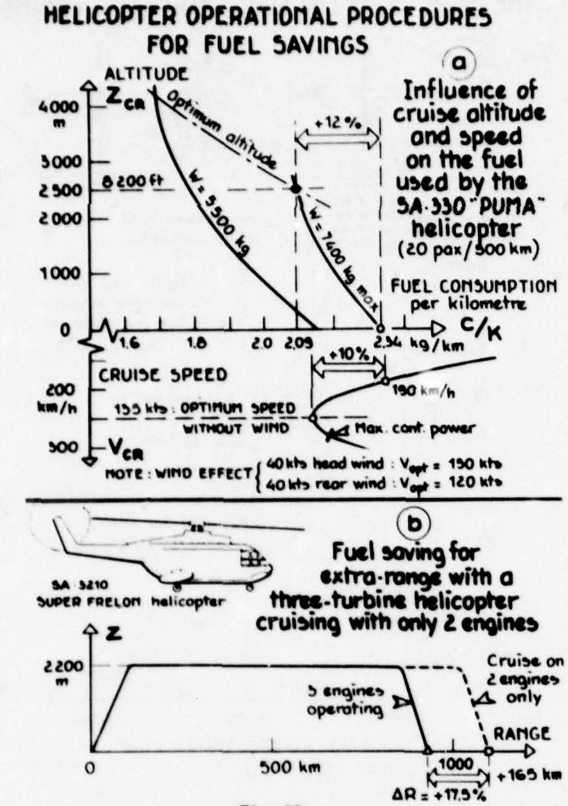


Fig. 40

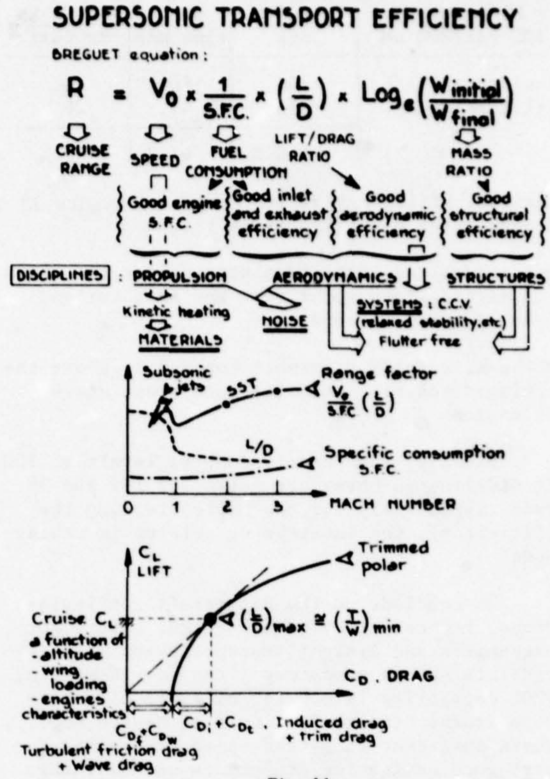


Fig. 41

A-7) TOWARDS MORE ECONOMICAL SUPERSONIC TRANSPORT

As a result of over a decade of intensive Anglo-French effort on both the airframe and the powerplant, the Concorde Supersonic Transport has convincingly desmonstrated its ability to cross the Atlantic (3200 nM) at Mach 2 with full payload (100 pax) and required reserves ; such achievement has proved to be very difficult and expensive, using the best technology available in the 1960's [64,65].

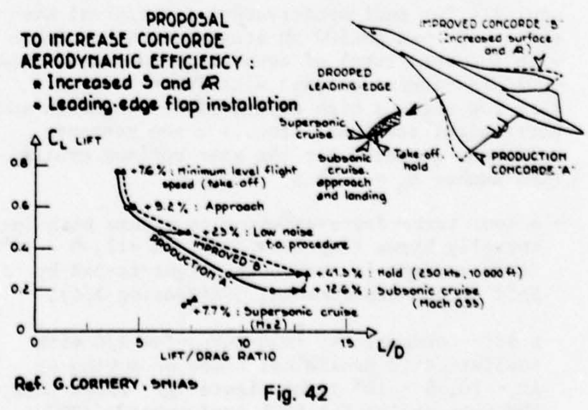
When compared with the "fuel efficiency" of existing or planned subsonic Transport A/C, the Concorde value appears very low, as shown on figure 2 , but it must be remembered that the Paris to New-York journey is now completed in half the time taken by his subsonic competitor.

As for the subsonic Transport already discussed, the future improvements in the SST efficiency depends upon the same technological advances (figure 41) on the various disciplines : propulsion, aerodynamics, stuctures/ materials and systems ; but, another vital problem will be the noise level reduction around airports, which needs further progress on both the engine design and the subsonic aerodynamic efficiency L/D (during take-off, climb, approach) ; finally the subsonic L/D must also be improved to reduce the fuel consumption during holding, and for imposed subsonic cruise above populated countries to avoid sonic boom.

As a first step, proposals have been made by airframe [SNIAS, 66] and engine [Rolls-Royce, 65] manufacturers for an improved "B" version of Concorde :

- on the aerodynamic side (figure 42), a small increase of the wing-tip surface and droop-leading-edge installation along the span lead to sensible L/D improvements both at low speed (which reduce the noise) and at cruise conditions (M = 0.93 and M = 2) ; furthermore, some minor changes in leading-edges and radome shape must also improve the supersonic wave drag;and structural weight savings are quite easy thanks to the introduction of composite materials (Kevlar, Carbone) ;

- on the engine side, an increase of the mass flow of the Olympus permits to improve the SFC and to reduce the noise around airports. In those conditions a 12 % fuel savings on the Paris/New-York mission was estimated.



Ref. G.CORNERY, SNIAS

Fig. 42

Another powerful way to improve the subsonic aerodynamic efficiency is the installation of a relaxed stability control system (A.C.T), which is particularly rewarding on the longitudinal mode of such a tailless A/C ; thanks to the installation of a fully redondant fly-by-

-wire system with three digital computers on the experimental Concorde n° 1, Aerospatiale was recently able to fly unstable in a large subsonic domain (figure 43) and to demonstrate a 14 % increase of the trimmed L/D for a 3 % C.G backward shift ; this improvement can be translated in a large increase of the permissible take-off gross weight (about 14 %) and/or an important thrust (and noise) reduction for a future SST configuration [67 and 42] ; in fact, all new U.S 2nd generation SST project are designed with such relaxed Stability Control.

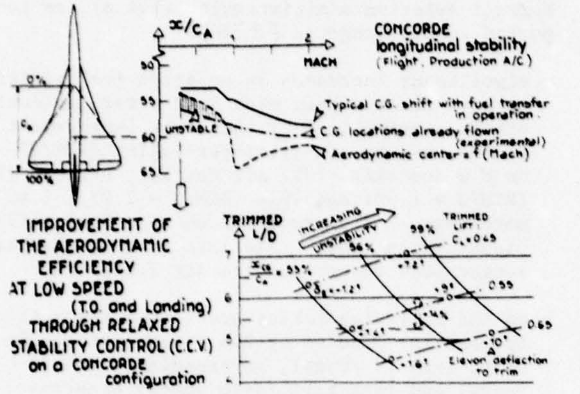


Fig. 43

About this second generation SST, it is interesting to summarize some of the trends already published :

- on the aerodynamic side, considerable progress has been obtained since few years through more and more elaborate aerodynamic computer programs, coupled with structural analysis, which permits a complete optimization of projects taking into account all design constraints ; a large part of these projects are asked by NASA to the major U.S manufacturers as a part of the Supersonic Cruise Aircraft Research (SCAR) program [68] ; their predicted supersonic aerodynamic efficiencies are illustrated on figure 44 , as a function of the cruise Mach numbers chosen by the various airframe manufacturers ; improvement in L/D to a value larger than 9 (instead of 7.3 for Concorde) seems technically possible in ten years or so for slender shapes with a well designed propulsive nacelles and fuselage integration.

- for the size, all the projects have a much larger capacity, around 280 passengers instead of 100 for Concorde,

- and finally their range is sufficient for a Trans-Pacific service (4000 nM or more) ;

- but the best cruise Mach number is still controversial - between M = 2.2 (where aluminium alloys are used for a large part of the structure) and M = 2.6 (where mainly titanium alloys must be used).

- About the best propulsion system for such projects, the airport environmental regulations will impose lower jet velocities than on reheated Concorde nozzle and perhaps the use of efficient noise suppressors ; several solutions are proposed :

  - a derivative of the Concorde-Olympus engine with a fan of BPR between 1 and 1.7 [9,65] ,

  - variable cycle engine (V.C.E), a "magic" propulsion system which performs as a straight turbo-jet cycle at supersonic cruise regime as a turbo-fan cycle during subsonic operations ; such attractive concepts need years of basic and applied research before a possible service in the 1990's.

- About structural weight, new structural concepts and manufacturing methods, extensive use of advanced composite materials and active control systems promise significant empty-weight reduction, up to about 10 %.

All in all, this second generation SST can perform about twice the 6 % payload fraction of a Concorde, and still satisfy some future FAR 36 noise regulations ; such new SST, a logic follow-on of the unique Concorde experience, will be used on long-range routes where high productivity is cost-effective [69].

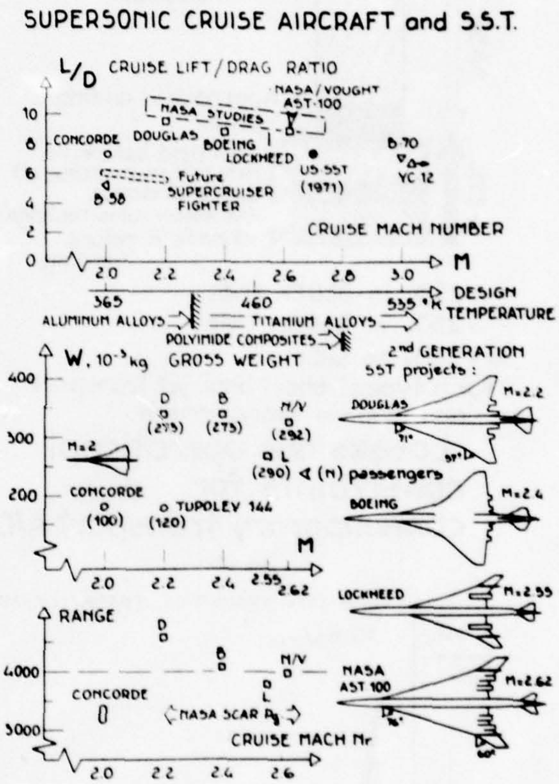


Fig. 44

B) NEW OPERATIONAL PROCEDURES

B-1) INTRODUCTION

When looking for ways of improving fuel efficiency, we must consider the total air transport system, and we shall see that, at the moment, a large part of the wasted fuel is due to the present air trafic control (ATC) constraints, to the imposition to follow special routes (to avoid noise sensitive area, etc...), and mainly to the delays arising from congestion ; figure 45 gives their typical effects on block fuel for a 500 nM stage length [10] : a penalty of 27 % in block fuel is given by these very frequent constraints (5 min. hold before take-off, non optimum cruise altitude, extra-distance for

airways and noise routings, and at last, 10 min. hold before landing) ; such energy waste is accompanied by penalties of 25 % in block-time and about 15 % increase in D.O.C ; these problems are unlikely to arise on every flight,and affect short-range flights much more than longer ones. However it appeared vital, at the beginning of the fuel crisis, to study the various ways to improve the operational procedures, the pay-off being of the same order of magnitude that from the most sophisticated technical improvements applied on the airplane itself.

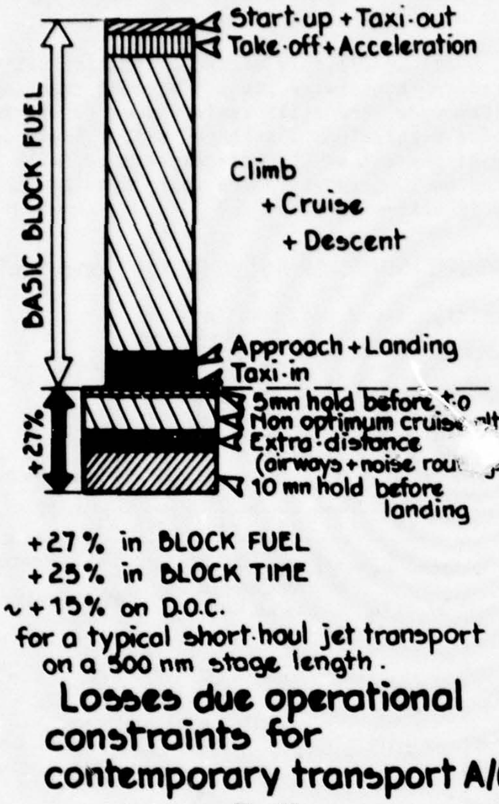


Fig. 45

A large effort has been successful in every country since the 1973's fuel crisis to reduce the most evident fuel wasting, and long-term plans have been prepared between regulatory agencies, airports management , aircraft operators and aviation industries to analyse future gains on fuel efficiency - and the price to pay, taking into account the key factors affecting the various options : technical, socio-political, economic, regulatory and operational.

At this stage, it seems interesting to summarize the impressive work done in U.S.A by the Federal Aviation Administration (F.A.A), as reported to U.S congress [2,86] :

- significant increases in aviation fuel efficiency have already been made just after the fuel crisis, examplified by the large improvement of the revenue-ton-miles-per-gallon (RTM/G) on U.S domestic civil Air Carrier, between 1972 (RTM/G = 1.90) and 1974 (RTM/G = 2.21), i.e. more than 16 % improvement on this fuel efficiency index (which take into account the passenger load factor and the air freight);

- on the following tables are listed the various options recommanded by F.A.A respectively in short term (2 years), intermediate term (3 years) and long term (4-10 years) programs ; some of these options have been already analysed in the previous sections ; some others, relative to operational procedures, are discussed in this chapter and are indicated on these tables with a mark (✱).

A first overview of potential fuel savings with some of these options on operational procedures is given on figure 46 , from a Lockheed study [26]for the NASA/RECAT program [71] ; the block-fuel consumptions are given as a function of the stage length for a typical tri-jet (Lockheed 1011 or DC-10) ; the near-term fuel savings can be obtained with the existing Air-Traffic-Control (- 3.4 %) but a larger gain (- 5.5 %) will be obtained after the long-term A.T.C management.

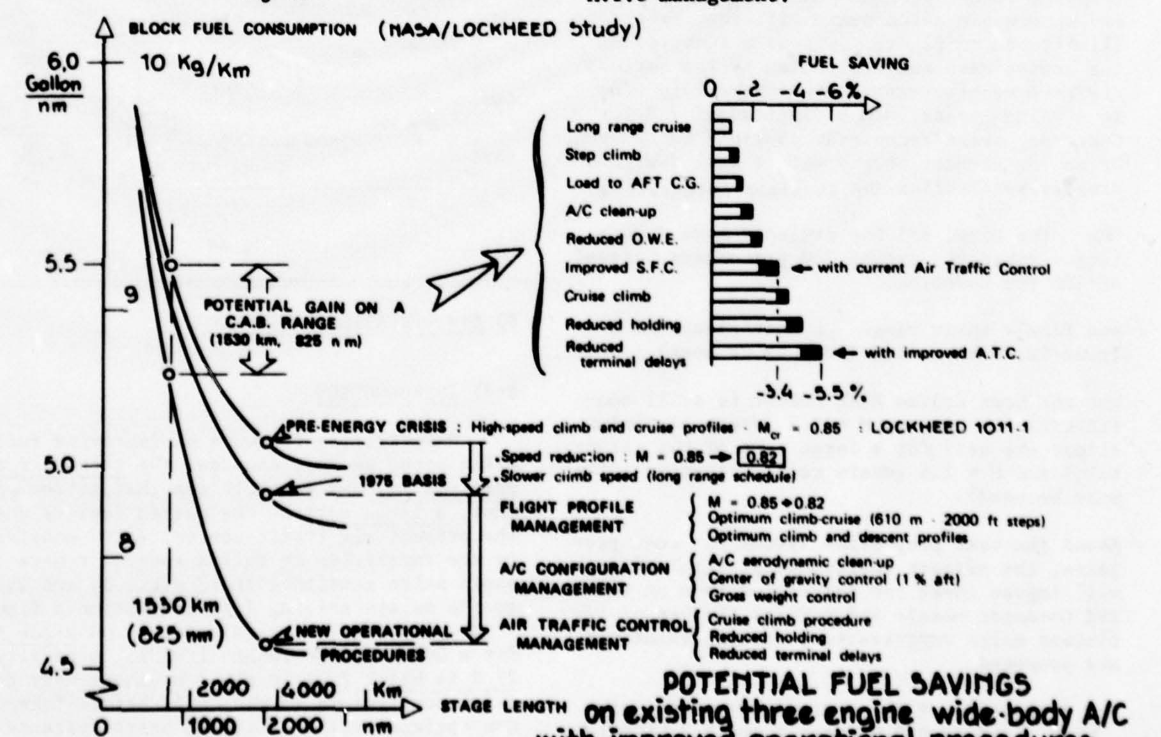


Fig. 46

Table I

FAA SHORT TERM PROGRAM OPTIONS

AND ESTIMATED GAINS ON FUEL EFFICIENCY

Increase on revenue ton × Miles per gallon $\Delta \frac{RTM}{G}$ %	Items :
	- Increase passengers per Aircraft :
1.1	- reseat existing A/C; * increase load factor through capacity restraint
	- Reduce gallon per hour by reducing delay
0.8	* fuel advisory departure procedures
0.2	* wake Vortex sequencing/avoidance systems; * decrease IFR spacing (// runways)
0.04	- use short temporary // runways during airport development
0.4	- construct short g^1 aviation runways at hubs airports
0.06	- snow-ice removal equipment
	- Reduce gallon per hour by improving Air/Ground operations :
0.2	* load to aft center of gravity
0.3	* reduce fuel tankering
0.2	* taxi on fewer engines
	- Reduce gallons per hour by optimum flight practices :
0.7	* optimum cruise speed
0.65	* optimum altitude/cruise climb
0.56	* optimum descent
	- Reduce gallons by minimizing distance traveled :
0.2	* expand use of area navigation (RNAV)
0.1	* maximize use of simulators
5.51 %	= Total estimated gains on the fuel efficiency (RTM/G = 2.21, in 1974 for the U.S domestic civil aviation, is taken as a basis)

Table II

FAA INTERMEDIATE TERM PROGRAM OPTIONS

for increasing fuel efficiency

1 - Performance measurement and evaluation program for JET-ENGINES (better maintenance to lower engine deterioration rates with use).

2 - Winglets (aerodynamic modifications to wing-tips, see section A-1-3)

3 - Electronic/mechanical guide in systems for A/C on the Airport-surface.

4 * Ground movement of A/C under alternate power sources (towing airplanes on the ground).

5 * Intermittent Positive Control (IPC) of Air Traffic (groundbased surveillance of all A/C, transmitting collision-avoidance)

6 * Discrete Address Beacon System (DABS) for airplane surveillance (ground-to-air data-link for rapid transmission)

7 * Microwave Landing System (MLS) (more flexibility and precise approach and departure paths)

8 * Airport Surface Traffic Control (ASTC) (new ground surveillance radars).

9 * Climb procedures in Terminal Control Areas (can eliminate the climb speed limitation and save fuel).

Table III

FAA LONG TERM PROGRAM OPTIONS

for increasing fuel efficiency

1 - Digital Electronic Propulsion Control Systems for Turbine Engines (reduction in control system costs, on fuel consumption and on A/C weight)

2 - Increase Thickness of Supercritical Airfoil in future A/C (see section A-1-4 and A-5)

3 - Active Control for Aircraft (ACT = CCV, see section A-3)

4 - Replacement Aircraft (new airframes and new turbo-fan engines, see section A-5)

5 - R/STOL Aircraft-optimum short-haul configuration (see section A-6)

6 - Improve Jet-engine Technology for fuel efficiency (see previous lectures)

7 - Spanloader (very large cargo flying-wing) design (see section A-5)

8 * Global Positioning System (GPS) for A/C navigation

9 * Alternative Taxiing Methods (powered landing gear, etc...)

10 * Other Upgraded Third Generation ATC System Improvements (automated flight service station program, DABS, IPC, Upgraded Automation, Airport Surface Traffic Control

11 - Laminar flow control (see section A-1).

Note) Some of the FAA options are not given in tables II and III because not directly connected with the paper.

B-2) FLIGHT MANAGEMENT

In this section, we shall examine the various options to save energy around the cruise regime (optimum cruise speed and altitude, climb and descent optimization, influence of the fuel reserves and tankering, en route navigation and control, etc...).

The most significant pay-off in flight profile management occurs during the airplane cruise ; for a long-range aircraft, cruise consumption reaches about 80-85 % of total block-fuel ; for fuel savings, airplanes need to be operated at optimum speed and altitude : a decrease in cruise speed and/or an increase in cruise altitude will reduce fuel consumption, as illustrated on figure 47-a, for the Boeing 727 case [2] ; a reduction in speed from M = 0.82 to 0.78 decreases the fuel usage by 3 % on a standard mission, and flying at FL 350 (35000 ft) instead of flight level 310 reduces the fuel consumption by 2.6 % ; the two effects are approximately additive (- 5.6 % fuel consumption).

For an Airbus A-300-B4, on the same 1000 nM stage length (block-fuel : 13.9 tons), the economical cruise speed is M = 0.78 and higher speeds are much fuel consuming for negligeable time savings :

$$\text{instead of } M = 0.78 : \begin{cases} M = 0.80, \Delta \text{ fuel} = +400 \text{ Kg}, \Delta t = -2 \text{min.} \\ M = 0.82, \Delta \text{ fuel} = +1200 \text{ Kg}, \Delta t = -5 \text{ min.} \end{cases}$$

In the case of a Lockheed 1011, on a 2000 nM route, the cruise speed reduced from M = 0.85 to 0.82 leads to about 2.2 % fuel savings.

In fact, almost all airlines have already instituted these procedures since several years ; but safety considerations have a bearing on how slowly a jet can be flown at high cruise altitude (because increased C_L values, near the transonic buffet placard ; and because increased A.T.C workload with mixed fleet at different cruise speeds.)

Several current transport A/C of the 70's were designed for high cruise Mach number -about Mo = 0.87 - and cruise speed reduction up to M = 0.80 (figure 47-b) is very beneficial to the energy efficiency (+ 10 %) for a typical short-haul A/C [72] ; on the same figure is given a new advanced 1980's project, designed for various cruise Mach numbers (with adequate propulsion and aerodynamic optimizations), to illustrate that advanced technology allows :

- to cruise at M = 0.95 with the same fuel consumption (but it is no more attractive since the crisis),
- or to cruise at the same M_0 = 0.80 with about 18 % more energy efficiency,
- or even to optimize the A/C at M_0 = 0.70 with a much larger gain on fuel, but with a poor productivity due to low block-speed.

In fact, this time penalty and the competitive disadvantage of low cruise speed is only significant for long-range missions : for example, reducing the cruise Mach number from 0.9 to 0.8 induces a significant 40 minutes penalty on the block-time of a North Atlantic crossing, but a very small 6 minutes penalty for a short 2000 km journey.

Concerning the optimum flight profile, it must be remembered that most of the fuel (about 90-95 %) is burnt during the climb and cruise portion of the flight, indicating that it is mandatory to maximize aerodynamic (L/D) and propulsive (V/SFC) efficiencies ; a continuous cruise-climb procedure (altitude increasing unversely proportional to the decrease of A/C weight) is the most economical one, but the ability to fly such a cruise-climb is limited by the current ATC: since the end of the 50's, separations rules lead the airplanes to fly at fixed flight levels; above the altitude of 29000ft (flight level FL 290), a 4000-foot altitude increment is required (ex : FL 310 - 350...in one direction and FL 290 - 330 - 370 in the opposite

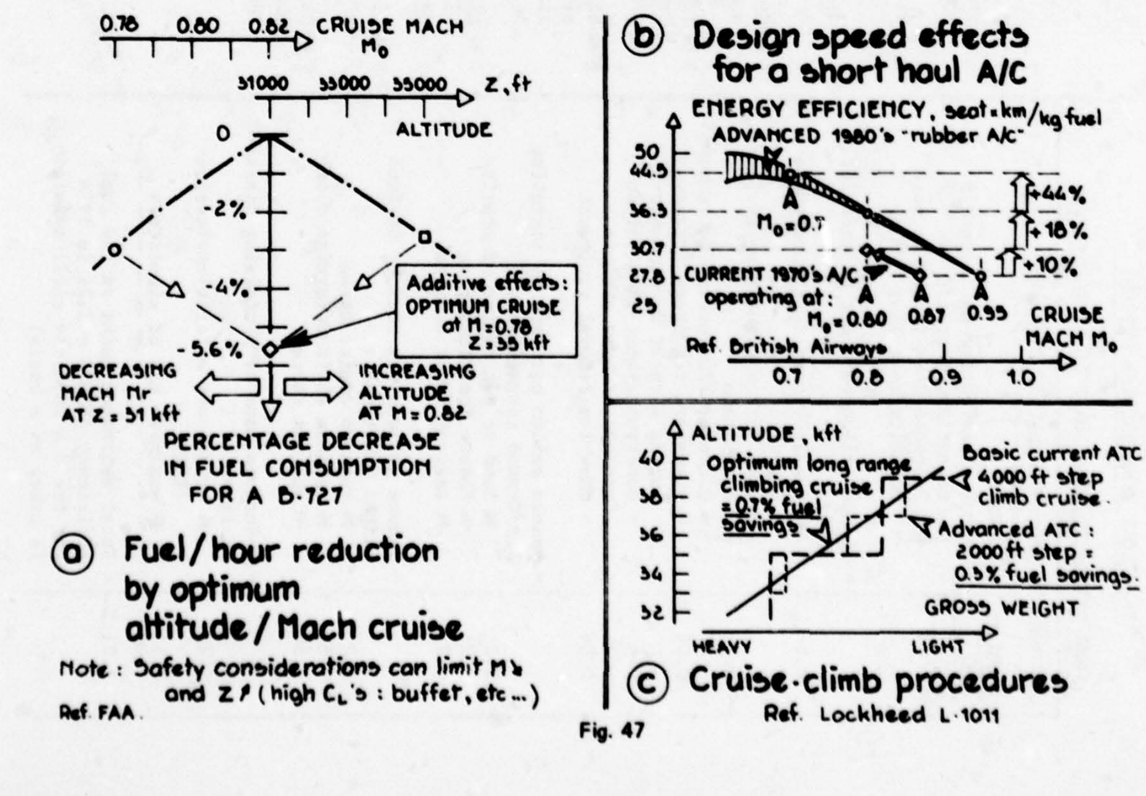


Fig. 47

direction). The actual traffic is concentrated on four main levels between FL 310 and FL 370 ; their utilization reaches 32 % of the total traffic (8 % each). These limitations lead also to congestion and "en-route" delays due to the application of horizontal separations rules.

Future advanced Air-Traffic-Control would allow at first a reduced vertical separation (only 2000 foot steps) and later a continuous cruise-climb procedure : figure 47-c, relative to the Lockheed 1011, shows that such operational improvements lead to fuel savings of 0.3 % and 0.7 % respectively.[26].

OPTIMIZED CLIMB SPEED

A reduction of the climb speed induces significant fuel savings ; for example, in the case of a NASA/Boeing study (200 pax/3000 nM/ M = 0.9/AR = 9 project), climb speed reduced from 375 to 300 Kts gives a 2 % and a 5.2 % block-fuel savings for a stage-length of 3000 nM and 1000 nM respectively ; it is concluded that this slower climb is most attractive for this short stage length where the climb lag consumption represents 1/3rd of the block-fuel. In the case of an Airbus A-300-B2 on a 1000 nM route, the low speed climb procedure (300 Kts) instead of 340 Kts saves about 155 Kg fuel (1.1 %).

PROFILE DESCENT

The amount of fuel used during the descent from cruise altitude to the ground is a low percentage of the block-fuel, even for a short range A/C (about 5 % B-F for a 1000 nM mission, and less for a long range mission) ; however, the intent of the procedure is to keep Aircraft at cruise altitude to a point where they can descend to the final approach path with the engines at idle ; we shall see later, in the Terminal Area procedures, that quite large fuel savings and noise reductions are possible during the final approach.

FUEL RESERVES

Another fuel saving potential would be a reduction of the required fuel reserves, as examplified by the following table, taken from a NASA-T.A.C/Boeing study (200 pax/3000 nM/M = 0.8):

Stage length	required reserves, %block-fuel (% B.F)	potential savings with 50 % reduction on required reserves :
3000 nM	25 % B-F	savings : - 6 % of B-F
1000 nM	70 % B-F	- d°- : - 7 % of B-F

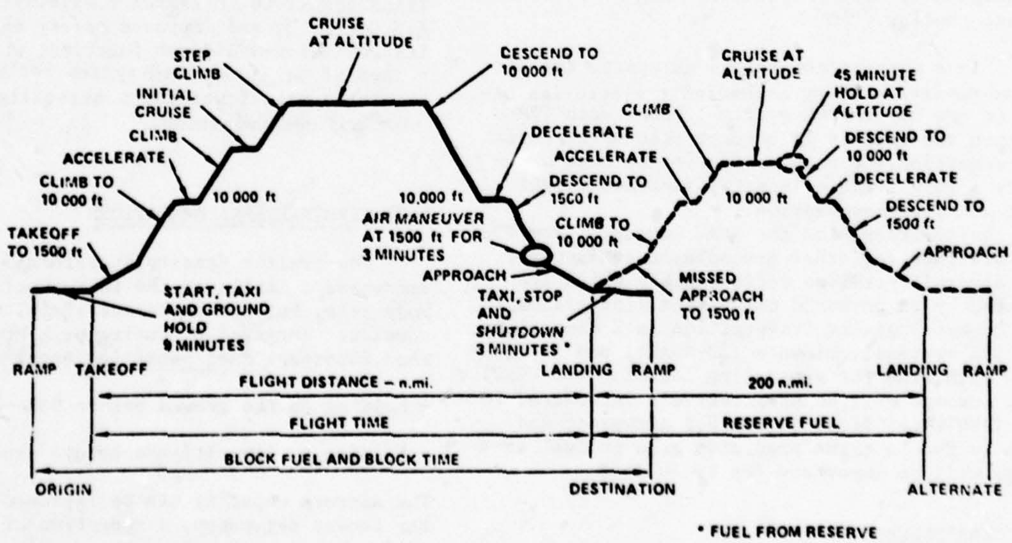
Note) The required reserves are function of the mission landing-weight and include 45 min. at long range cruise Z and M, a missed approach, plus a 200 nM diversion, (figure 48).

In the case of an Airbus A-300-B4 on a 1000 nM stage length, the usual fuel reserves are estimated at 5-6 tons, which cost about 400-500 Kg extra-fuel to carry ; better traffic control regulations would remove for example 1 ton of these required reserves, and would save 145t fuel per Aircraft/year !! [51].

FUEL TANKERING

On the other hand, if extra-fuel is taken aboard, for example 50 % more than the required reserves, there is a severe + 6.5 % block-fuel penalty to pay ; finally if the 3000 nM mission is performed with 2 intermediate stops (1000 nM) each), with no refueling at each stop to spend less time on the ground, the fuel penalty increases to about + 19 % of the block-fuel.

This "TANKERING" procedure is sometimes used by Aircraft operators because of differing prices and availability of fuel at various airports ; tankering is unefficient because of the fuel burnt to carry this surplus fuel ; for example 900 Kg of tankered fuel require an additional 55 Kg in fuel consumption which represents about 1 % of the block-fuel on a 500 nM/B-727 mission. In the following table, are listed the impact of tankered fuel on consumption :



TYPICAL MISSION FLIGHT PROFILE AND REQUIRED RESERVES

Fig. 48

A/C type	B-727	A-300	B-747
range, nM	1000	2000	3000
extra-fuel, Kg, for tankering 1 T	130	200	265
% block-fuel	1.5 %	0.75 %	0.50 %

For a long-range A/C, the fuel efficieney (seats x Km/Kg fuel) reaches a maximum and then decreases slightly for very long stage lengths ; this explains why in this case, a mid-point stop for refueling is advantageous for fuel savings, but not for the Airline's D.O.C and productivity, because of the flight time increase ; the following table gives these fuel savings as a function of the trip length with a mid-point stop instead of a non-stop flight [6].

Total trip length, nM	% fuel saved with mid-point stop
4000	4.6 % block fuel
5000	8.3 % block fuel
6000	10.7 % block fuel

LOAD TO AFT CENTER OF GRAVITY

Aircraft trim drag is minimized when the A/C C.G. is at the aft limit, specified "safe" for aerodynamic stability on a current configuration ; we have seen previously (section A-3-7) that, for a civil transport A/C, a 5 % aft C.G. shift leads to about 1 % fuel saving ; larger gains are estimated on military cargo and bomber A/C.

AREA NAVIGATION (RNAV)

Use of RNAV permits establishment of direct routes between preselected points rather than having to fly along prescribed airways or requiring radar vectoring by controllers to achieve direct routing. [73].

In a current controlled airspace, the Airplane navigates along segmented trajectories based on use of VOR/DME system ; above each VOR station the traffic is concentrated up to a risk of congestion, and such navigation becomes a penalty : larger route lengths, increased flight time and fuel consumption.
On the contrary, with the RNAV concept, from VOR/DME stations (or other groundbased equipement) the aircraft receives radio signals which are treated by an on-board calculator (integrated in the cockpit) giving its position in 2 dimensions, or with vertical guidance (3D-RNAV), and furthermore with time for scheduling location (4D-RNAV) ; this concept will be progressively introduced in the 1980's, at first in the U.S airspace, and then in Europe ; the predicted gain on fuel savings will be important (up to 10 %)

OVERSEAS FLIGHT

Various systems have been developed for overseas flight, which give a much better precision to follow a prescribed (shortest and quickest) route without ground surveillance :

- Inertial Navigation System (INS)

- OMEGA radio-navigation system [74,75];

these two concepts are fully operational today ; NAVSTAR (NAVigation System with Time And Ranging)/ G.P.S (Global Positioning System)[76,77,78], on the contrary, is a new sophisticated concept using 24 satellites in non stationary orbits (12-hour orbit) to achieve global-high accuracy position finding ; being presently developed for U.S military A/C, this system could become the basis for the 4th generation ATC (supposed to be fully operational at the end of the 80's) ; it requires installation of new - and still expensive - electronic equipment.

The pay-offs of very precise navigation systems are important for the long-range flight economy (fuel savings on direct routes, reduction of the prescribed separation between airplanes, etc...)

AIR TRAFFIC CONTROL (ATC)

The current system needs to be improved : first, primary surveillance radar has permitted A/C location to reduce separation to 5 nM for "en route" flight and 3 nM in terminal area ; introducing a secondary surveillance radar (SSR) has given new informations to the controller (A/C identity and altitude) ; but due to the increased traffic density, the "garbling" phenomena (loss of information from two planes) has appeared. New systems for Airpspace surveillance are now developed in U.S.A (Discret Address Beacon System : DABS), in U.K (ADSEL : ADdress SELective) and in France (SRSSR: Stochastic Response Secondary Surveillance Radar) [74,75].
The DABS concept (Discret Address Beacon System) will provide the basis for the Intermittent Positive Control function through a ground-to-air data-link for rapid transmission of control messages ; such system will permit improved surveillance of future close-spaced air navigation routes in dense terminal areas and parallel approaches.

Fuel savings results from more direct routings, thanks to increased flexibility of the A.T.C [2]; and improved safety will come from its collision-avoidance function, which will be a part of an integrated system including also the three main functions : surveillance, navigation and communication.

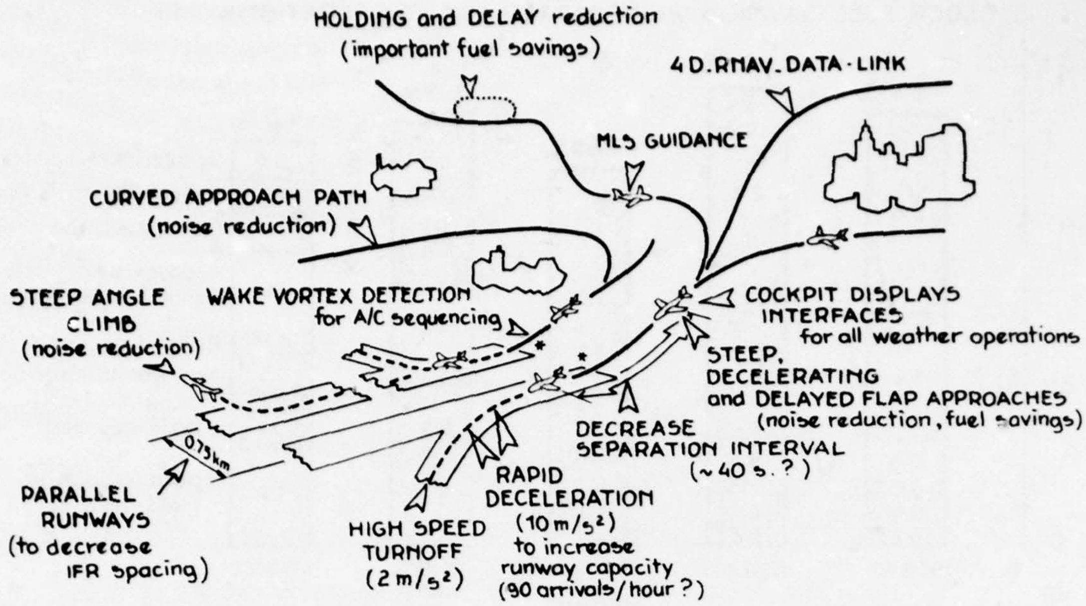
B-3) TERMINAL AREA OPERATIONS

The traffic density in terminal areas has decreased a little at the introduction of wide-body jets, but now increases again, up to a complete "congestion" during peak hours traffic ; then, important fuel penalties occur during :

- holding on the ground before take-off,

- holding at low altitude before landing.

The airport capacity can be improved by a shorter runway occupancy, a reduction of the separation between two aircraft, and various new procedures during take-off and landing ; figure 49 sums up the improvements which are planned in a future high capacity terminal [79] environment.



FUTURE HIGH CAPACITY TERMINAL AREA OPERATIONS

Fig. 49

In the short-term FAA project, landing capacity could be increased by reducing IFR spacing or runway occupancy-time thanks to parallel runways, rapid deceleration and high-speed turnoff.
Later on, a large pay-off on fuel consumption due to a reduction on separation intervals between two A/C will occur by using wake vortex detection : a Wake Vortex Avoidance System (WVAS) may provide the basis for increased capacity and improved safety.
The arrival to the final approach glide-path will be improved by use of new systems like 4D-RNAV and data-link, Microwave Landing System (MLS) and curved approach paths for noise avoidance over populated areas, cockpit displays interfaces to permit all-weather operations, and the use of steep/delayed-flap approach to save fuel and reduce noise.

HOLDING

Certainly, one of the primary causes of fuel wasting is holding delays. It is interesting to give the level of those delays for the U.S civil Air Transport in 1975 [2] by source :

	hours	%
- Ground delay (taxi-in + taxi-out)	251290	49.7
- Airborne delay	237090	46.9
- Gate delay (ATC clearance, weather, snow...)	16925	3.4
Total:	505305	100 %

Notice that delay is almost equally divided amongst ground and air.

Ground delay is due to extended ground circuits and traffic congestion which obliges Aircraft to queue in line, before take-off. An improvement can be achieved by keeping the Aircraft at the gate (engines shut down) ; the clearance for taxiing will be given by the control when the ground delay is minimum (5 mn flor example). But these procedures are difficult to apply because of the airlines gate departures schedule, or because the gate is attributed to another Aircraft on arrival.

Airborne Delay : usually, holds were performed following special patterns called "racetrack patterns" at low altitude (5000-7000 ft). Fuel penalty is important and amplified by maneuvers (4 % consumption increase). Holds performed at 15000 feet in a clean configuration rather than at 5000 feet with extended flaps (2°-5° to reduce the Aircraft speed) can save approximatively 4 % of the wasted fuel. When terminal delays are expected at the destination airport, the linear hold technique can be used with the control authorisation.

A new procedure : Fuel Advisory Departure (F.A.D) has been studied by FAA to improve the current situation and would provide a more efficient distribution of delay to users by encouraging ground instead of airborne delays (a B-727 consumes 58 Kg fuel/minute in cruise instead of about 25 Kg on the ground, and much less if holding at the gate) ; such redistribution of delay can be handled by computer techniques ; one F.A.D exercise, made by F.A.A [2] in 1976 at the Chicago O'Hare - the most crowded airport in the world - hase shown an encouraging saving : 490000 Kg fuel in a 6-hour test ! On figure 50, [80] expected reduced terminal delays appear as a large part of the benefits possible with the future Air-Traffic-Control, mainly for short range Aircraft (2.5 % for a DC-9-30), because a large part of the flight time is spent in Terminal areas ; by the same time, less "en route" delay will be necessary (1.6 % for DC 9-30) ; notice also that shorter delays may lead to reduce the required reserves, i.e. a "snowball effect" on fuel savings.

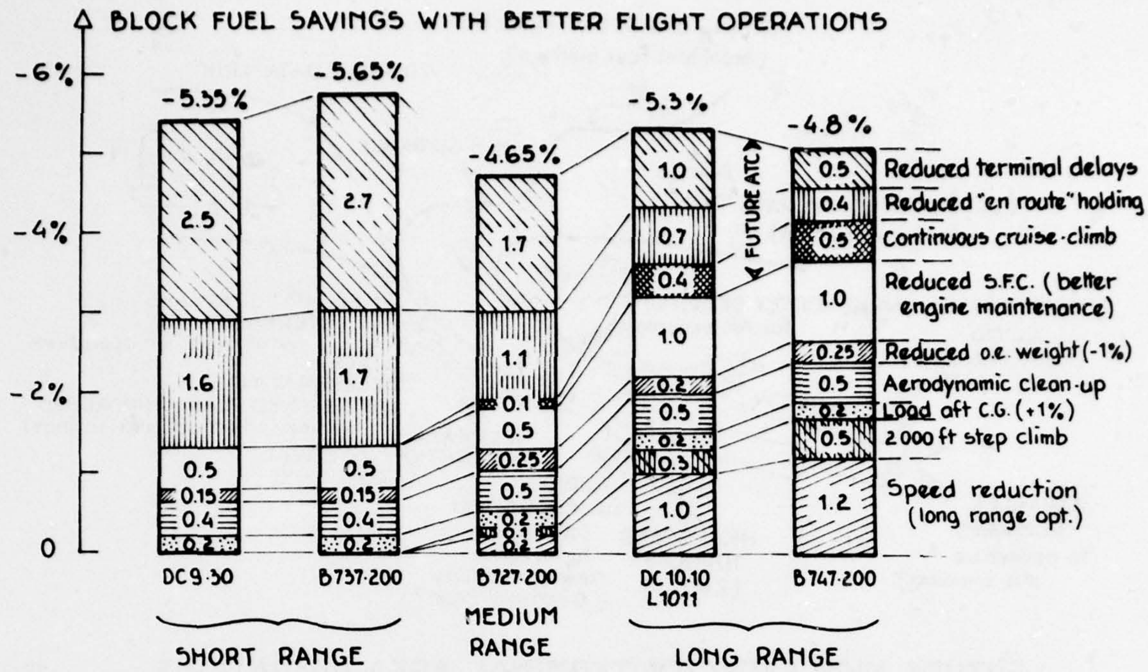


Fig. 50

WAKE-VORTEX AVOIDANCE

Separation standards between aircraft have increased in 1970 to 4-5 nM (in USA) for landing (instead of 3 nM) and up to 6 nM in the most stringent case (U.K, 1974 : when a small aircraft follows a heavy one).
This increase is due to the presence of strong wing-tip vortices generated by large aircraft. Intervals may be safely reduced by using a wake-vortex detection system to know the presence and areas of vortices. Such a detection system can be installed before the runway threshold but also on-board the aircraft ; then increased landing capacity would also be obtained by a proper A/C size sequencing ; finally, flight and wind-tunnel research are in progress to reduce the far-field vorticity behind large A/C by an appropriate distribution of flaps and/or spoilers deflections along the wing span [81].

FINAL APPROACH PROCEDURES

Usual jet-transport stabilized landing approach is performed with the "classic" ILS (Instrument Landing System), with a glide capture at approximately 15 Km from the runway threshold (figure 51-a); a conventional descent is flown with extended flaps and gear-down inducing a large drag, i.e. quite high thrust level is needed. Such a configuration is fuel consuming and noisy.

In the last few years, improved procedures were developed, at first to reduce noise around Airports and more recently to save energy. Figure 51 illustrates the compared fuel consumption and noise contours results from a Boeing-NASA study about different B-727-200 approaches [82]; (tests were also performed at NASA-ARC with a CV-990, [83]).

A first improvemant was the "reduced flap" approach (figure 51-b) developed and instituted by Air Transport Association (ATA) members airlines ; but a major gain-both on fuel consumption and on noise level- can be obtained with a two-segment approach procedure:- 44 % of fuel is saved upon the reference ILS approach ; and a reduction is obtained on the noise area to 1/3 the size of that generated by the B-727 with a current "reduced flap" procedure.

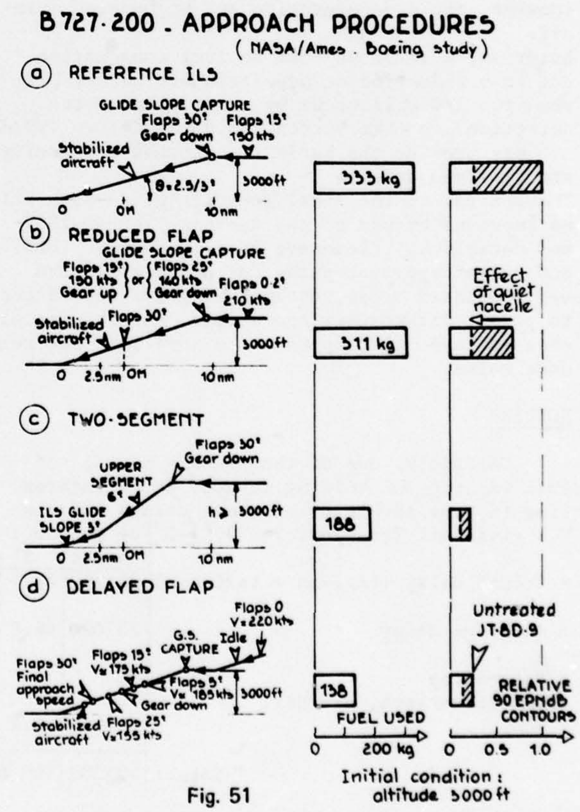


Fig. 51

The glide capture is operated closer to the runway threshold than for the other procedures. The two-segment approach proposition has been rejected by FAA in november 1976 (Federal Register Docket n° 15030 - amendement 91-134)

The most economically interesting approach seems to be the decelerated one, or delayed flap

approach, already applied by various Airlines in agreement with ATC authorities ; figure 51-d illustrates this approach which begins at idle regime and clean configuration ; then the pilot decelerates progressively by sequencing flap deflection (5°-15°-30°) and putting gear-down at prescribed speeds;the delayed approach allows about the same noise relief but more fuel saving (≃ 25 %) than two-segment approach.

Such sequencing is a good case for introduction of a mini-computer in the loop to optimize this procedure and save pilot workload : such a Decelerated Approach System (DAS) is already flown on the Airbus, where the computer takes care of the autothrottle and gives visual indications to the pilot for successive flap settings and gear-down orders: such procedure, applied on the A-300-B2 gives a 120 Kg fuel savings when compared with a conventional 1.3 Vs/ flap-down/gear-down approach from 2500 ft to the ground (fuel economy represents more than 1.5 % of the 500 nM stage length block-fuel.)

TAKE-OFF AND CLIMB PROCEDURES

Take-off portion of the baseline flight profile (up to 1500 ft) is too short to estimate some potential fuel savings ; usually take-off is concerned with the noise abatement procedures: thrust settings are high to permit the A/C to fly over populated area at better altitude ; then the pilot reduces the thrust level for a while : these thrust changes are not fuel efficient.

Another procedure consists in making a turn as soon as possible to fly over water (ex : Los Angeles) : Departure trajectories are lengthened and more fuel consumed.

If noise abatement is not a limitation factor, then take-off with reduced flap settings and power settings may save some fuel (taking into account field length and gross weight limitations).

Current A.T.C restrict climb speed to 250 Kts below 10000 ft altitude ; if such a limitation can be eliminated in terminal control areas, the jet airplanes would save significant fuel by climbing at their optimum speed which generally exceeds 250 Kts.

LANDING

During the landing phase, the fuel penalty occurs when a missed approach must be decided. Weather conditions are usually the basis of such decision and a diversion is necessary : more fuel is consumed and time is spent to reach the diversion airport where safe landing is possible. It is for safety reasons that operational minima (minimum weather conditions) must be applied ; large energy and time savings have resulted from the introduction of various automatic landing systems to operate under category III conditions (on Air-Inter Airbus,the decision height is 7.6 m and the runway visual range only 125 m.).

TERMINAL AREA NAVIGATION AND GUIDANCE

The impact of AREA NAVIGATION will be important in terminal area because of significant reductions on holding delays, on time and distance flown and on pilot workload.

An FAA estimate [73] gives a fuel saving up to 385 x 10^6 gallons (1187 x 10^6 Kg) for the U.S Air carriers in 1984.
Another advantage of RNAV will be to provide approaches to non-instrumented runways.

The MICROWAVE LANDING SYSTEM (MLS), still under development, is based on a time-reference scanning beam technique ; MLS will provide a greater degree of operational flexibility and precision than existing ILS for approach (and departure) paths of civil and military A/C ; MLS installation will be possible at sites not now serviceable with ILS, due to terrain conditions : furthermore, MLS will make possible steeper approach paths, to meet V/STOL requirements for example ; its greater precision will also make possible curved trajectories and then close-spaced parallel approaches, i.e. increased capacity (and fuel savings) for congested Airports.

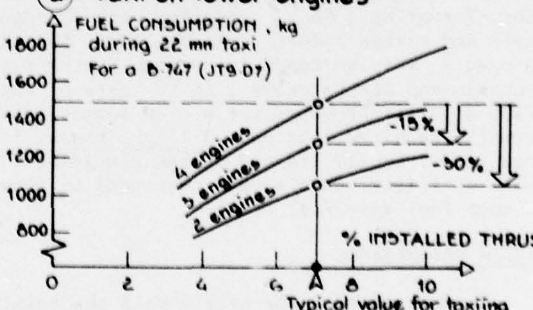
GROUND OPERATIONS

To improve the Airport Surface Traffic Control (ASTC), new ground surveillance radars are being developed to achieve automatic A/C tracking and ensure safe and efficient movement on the ground even with poor visibility (reduced delays, avoidance of collisions between A/C and other vehicules, etc ...).

Another important aspect of ground operations is the large amount of fuel consumed (increasing Airport pollution) for this A/C ground traffic ; several improvements are possible : taxi on fewer engines and powered landing gear.

GROUND OPERATIONS

(a) Taxi on fewer engines



(b) Powered landing gear

SNIAS A/C project / Medium range / 2 ten tons engines
TOGW ~ 76 tons

	Taxi with 2 ENGINES	Taxi with POWERED WHEELS
TAXI OUT Fuel consumption	252 kg	125 kg
and time	13 mn	14 mn
TAXI IN Fuel consumption	93 kg	13 kg
and time	5 mn	5 mn
TOTAL	345 kg 18 mn	138 kg 19 mn

Extra taxi time : 1 mn
Fuel gain with powered wheels : -197 kg
(with 10 kg penalty due to the system weight)
GAIN = -4.6 % BLOCK FUEL ON 500 nm STAGE LENGTH

Fig. 52

By taxiing to - and from - the gate on fewer engines, considerable fuel can be saved ; most operators have already adopted this practice, since the fuel crisis, on their three and four engine A/C ; figure 52-a shows the large amount

of fuel saved on a B-747 when one or two of its engines are inoperative for ground maneuvers : about 450 kg fuel saving for 2 engines, i.e. 30 % economy for a typical 22 minutes taxi-cycle-landing/take-off ; significant fuel savings are also obtained on three-engines (15 %).

Alternative far-term taxiing methods are under study : powered landing gear, cable tow, articulated tractors, etc ... ; the most attractive because autonomous, is the powered landing gear concept, studied by various manufacturers ; figure 52-b gives some results from an Aerospatiale study [51] based on a medium-haul, 76 tons, twin-jet (CFM 56) project : on each mean-gear is installed a hydraulic motor which drive the wheels through tire friction-rollers ; the hydraulic power is supplied by the Auxilary Power Unit (A.P.U.) ; the extra weight of the system is about 240 kg (equivalent 10 kg fuel penalty) ; the calculated fuel saving is impressive : about 200 kg (i.e. 4.6 % block-fuel on a 500 nM stage length) ; the design ground speed : 25 km/h, is a little lower than usual (current mean value : 35 km/h).

B-4) A/C OPERATORS MANAGEMENT

USE OF A/C SIMULATORS

Air carriers are now utilizing more and more simulators for flight crews training and checking, to reduce the cost of actual flight operations and save fuel (about 25000 gallons/per year/per A/C for wide-body) ; FAA estimates that 177000 take-offs and landings are avoided annually, enabling U.S Airlines to save about 170 million gallons ; the French Organization "*Aero-formation*" [84], *connected with Aerospa*tiale and Airbus Industrie in Toulouse, has developed a very successful training system for Concorde and Airbus crews ; in the case of the A-300-B, 15 flight hours for a crew formation are normally required, but only 3 flight hours, if crew is previously trained on the simulator ; these 12 flight hours saved correspond to about 66 tons fuel saved/per crew).

BETTER MAINTENANCE

Engines account for nearly half the total A/C maintenance costs ; investing advanced technology to improve engine reliability and maintainability has also a pay-off on fuel consumption [10].(see previous lectures).

On the airframe side, the "ageing" phenomena of A/C fleet leads to a continuous increase of the empty-weight and to a progressive deterioration of the airframe skin surface ; of course, both trends are fuel consuming ; for example, Air France has established [85] that the empty-weight of most A/C of its fleet has increased by about 2 tons along the A/C life : each supplementary ton increases the hourly fuel consumption by about 33 kg on a B-747 and by 150 kg on a Concorde !

On the other hand, we have seen (section A-1-2) how large is the pay-off of periodic "clean-up" operations to reduce airframe parasitic drag - and fuel waste.

BETTER LOAD FACTOR

In the previous sections, we have always quantified fuel savings with an "ideal" index : seat/Km/Kg fuel which supposes a 100 % load factor : in fact, this load factor slowly increases since the fuel crisis but is still very low : about 55 % for the U.S Airlines in 1976, and not so different for other countries.

A better adjustement of A/C capacity and frequency to each market is the evident - but not so easy - solution to increase Airlines load-factor.

Even a small gain on this index can save a large amount of fuel, as shown by the following estimates : taking as a basis the 55.8 % load-factor obtained by the U.S domestic Trunck Airlines in 1976, the amount of fuel saved by higher L.F was estimated [86] :

Load Factor		Fuel savings
instead of a current L.F = 55.8% in 1976 for U.S domestic Airlines	L.F = 60%	- 479.10^6 Gallons * (1.480.000 tons)
	L.F = 70%	- 1387.10^6 Gallons * (4.278.000 tons)

* Note that the U.S domestic Air carriers have consumed 8233 x 10^6 Gallons in 1977 [70].

To conclude, a ~ 14 % increase of the mean load factor represents a much larger energy saving (~ -17 %) than the best technological improvement.

It is a very frustrating conclusion for a technician ... except when a Concorde, with a 100 % load factor, appears more fuel efficient than an old B-707 A with a load factor less than 47 % on a Paris-to-New-York trip [85].

B-5) EFFECTS OF ENVIRONMENTAL NOISE CONSTRAINTS ON A/C CONCEPT AND FUEL ECONOMY

In most countries, Regulatory Agencies have agreed on Air Traffic and Airspace management operational procedures to control noise at - and around - airports. Some of these procedures are fuel consuming, for instance when they oblige to increase flight distance - and time - to avoid residential neighbourhoods during take-off and landing.

Some other procedures, like climb over residential areas with reduced power, or optimum descent and approach trajectories with low drag/clean A/C configuration - i.e. low thrust -, not only abate noise but conserve fuel.

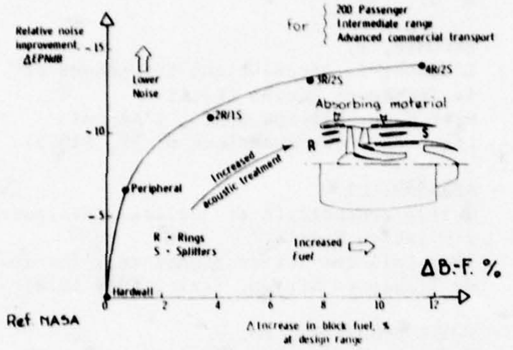
In the first case, some too severe A.T.C noise abatement may produce a large fuel wasting (in the case of Seattle Airport, in U.S, such FAA rules resulted in an estimated additional 2.2 million gallons (6800 tons) of fuel yearly, [86], and increased the average flight time by 5 to 9 minutes for each Aircraft)

With regard to the noise regulations, an agreement was reached in 1969 between the countries of the International Civil Aviation Organization (I.C.A.O.) : this agreement recomands precised noise level limits (measured in Effective Perceived Noise Level in decibels, EPNdB) at three locations near the runway : take-off, side line and approach.

These levels were a function of the A/C take-off gross-weight only : but a new proposal for an "annexe 16" amendement (to be applicable

from August 1978 if agreed) ask for a little lower noise levels, now a function of A/C gross-weight and also of the number of engines ; figure 53-b illustrates, in the take-off case, the evolution of these noise limits with years ; the results of the noise measurements for most of current subsonic transport show a continuous noise level decrease, at first with the introduction of low BPR and then large BPR engines.

(a) Energy implication of noise reduction



(b) More stringent noise regulations

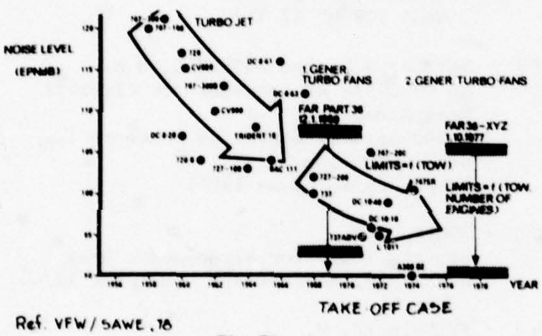


Fig. 53

With the development of the third generation high by-pass ratio engines, fuel economy was obtained in addition to a much quieter environment (see the A-300 B on figure 53-b), compared with older jets which are still in service (turbo-jets and low by-pass ratio engines); for these later Aircraft categories, some acoustic treatment of the engine nacelle walls have been necessary to cope with the first phase of noise regulations ; such treatment have a small weight penalty.

More stringent rules will probably be introduced into service in the mid-1980's, to some 10 EPNdB below the existing one's ; achievement of such goal will be much more costly with our current technology : figure 53-a illustrates the corresponding increase in block-fuel for a typical advanced wide-body transport [87]: 4 % increase in fuel for a noise abatement of about 11 EPNdB ! This penalty originates from the extra-weight and from the parasitic losses due to acoustic materials (applied to walls, and on special rings and splitters inside inlet and exhaust).

However, new technologies may solve this noise penalty in two different ways :

- extensive use of structuraly integrated composite materials to design the nacelle, in both acoustic and non acoustic regions, with no more economic or fuel penalty [87,16].

- propulsive nacelle located above the wing to take advantage of the shielding effect of the wing to reduce the fly-over noise ; we have seen previously that such a concept has also potential pay-offs for drag reduction and for high lift generation (section A-4-1).

Is it reasonable to push farther the noise abatement limits ?

It seems not, because we shall reach such a low noise level from the engines that the aerodynamic noise begins to intrude ; fly-over acoustic measurements have been made in flight during approach of several wide-body type A/C, showing that the aerodynamic noise generated by flaps and gears-down have about the same level than an hypothetic (FAR 36 - 10 EPNdB) regulation ! And it seems very difficult to avoid this aerodynamic noise...

To conclude with the impact of noise abatement regulations on A/C energy conservation, it appears that very large noise reductions have been obtained with the current wide-body A/C equipped with high by-pass ratio engines, accompanied by a much better energy efficiency ; it will be again improved on the next generation of transports using CFM-56/JT-10D engines to replace the first generation turbo-jet A/C.

Before imposing more stringent noise regulations, it seems wise to evaluate trade-offs between noise abatement and fuel conservation/Aviation economy objectives.

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CATEGORY 1 – ENERGY CONSERVATION IN AIRCRAFT PROPULSION

SAWE Paper 1124 76/05/00 77A12192
AIR TRANSPORTATION ENERGY EFFICIENCY – ALTERNATIVES AND IMPLICATIONS
Williams, L.J.
(NASA, Ames Research Center, Moffett Field, Calif.)
National Aeronautics and Space Administration. Ames Research Annual Conference, 35th, Philadelphia, Pa., May 24–26, 1976, 25 p.

Results from recent studies of air transportation energy efficiency alternatives are discussed, along with some of the implications of these alternatives. The fuel-saving alternatives considered include aircraft operation, aircraft modification, derivative aircraft, and new aircraft. In the near-term, energy efficiency improvements should be possible through small improvements in fuel-saving flight procedures, higher density seating, and higher load factors. Additional small near-term improvements could be obtained through aircraft modifications, such as the relatively inexpensive drag reduction modifications. Derivatives of existing aircraft could meet the requirements for new aircraft and provide energy improvements until advanced technology is available to justify the cost of a completely new design. In order to obtain significant improvements in energy efficiency, new aircraft must truly exploit advanced technology in such areas as aerodynamics, composite structures, active controls, and advanced propulsion. ABA V.P.

SAE Paper 760538 76/05/00 76A36606
AIRCRAFT PROPULSION – A KEY TO FUEL CONSERVATION: AN AIRCRAFT MANUFACTURER'S VIEW
Stern, J.A.
(Douglas Aircraft Co., Long Beach, Calif.)
Society of Automotive Engineers, Air Transportation Meeting, New York, N.Y., May 18–20, 1976, 18 p.

A range of possible approaches to fuel conservation is examined. The fuel contribution to direct operating costs, aircraft operations and maneuvers designed to conserve fuel, aircraft design variants, modifications, and refittings capable of aiding fuel conservation are discussed. Advantages of turbofan and turboprop derivatives of basic aircraft designs are examined. The RECAT (Reducing Energy Consumption of Commercial Air Transportation) program is outlined. The possible impact of recent technological advances in aircraft design (supercritical airfoils, optimized wing geometry, longitudinal stability augmentation, composites, new metallic structures) on fuel conservation is examined. ABA R.D.V.

SAE Paper 760537 76/05/00 76A36605
FUEL CONSERVATIVE POTENTIAL FOR THE USE OF TURBOPROP POWERPLANTS
Foss, R.L.; Hopkins, J.P.
(Lockheed-California Co., Burbank, Calif.)
Society of Automotive Engineers, Air Transportation Meeting, New York, N.Y., May 18–20, 1976, 15 p.

The turboprop propulsion system may offer the air transportation industry one of the most significant means of achieving reduced operating costs through large reductions in fuel consumption. The prop-fan high speed propeller concept allows the superior propulsive efficiency exhibited by the turboprop to be extended to cruise speeds compatible with current turbofan aircraft. Comparison of a prop-fan and a turbofan powered aircraft, each designed on an equal technology, equal mission and equal comfort basis is used to illustrate the prop-fan benefits. Accountability for the differences in the installation requirements of each propulsion system is included. The significant fuel and cost improvements shown for the prop-fan aircraft call for an extensive research program to verify the performance of this propulsion concept and to provide a data base that will allow incorporation in future aircraft. ABA author.

SAE Paper 760535 76/05/00 76A36603
FUEL CONSERVATIVE PROPULSION CONCEPTS FOR FUTURE AIR TRANSPORTS
Gray, D.E.; Witherspoon, J.W.
(United Technologies Corp., Pratt and Whitney Aircraft Div., East Hartford, Conn.)
United Technologies Corp., East Hartford, Conn. Society of Automotive Engineers, Air Transportation Meeting, New York, N.Y., May 18–20, 1976, 11 p. NASA-sponsored research.

The results of a feasibility study of proposed fuel conservative propulsion concepts for air transports with an assumed Mach 0.8 cruise capability are summarized. All engines considered are based on projected 1985 technology. Operating fuel requirements, propulsion operating costs, and noise characteristics are compared with those of a present technology turbofan engine. The study indicates that an advanced Brayton cycle gas generator in a turbofan engine or geared to an advanced multibladed, small diameter propeller with a projected efficiency of 80% at Mach 0.8 offers the greatest potential for energy conservation. ABA C.K.D.

74/00/00 74A38898
AIRCRAFT FUEL CONSERVATION: AN AIAA VIEW; PROCEEDINGS OF A WORKSHOP CONFERENCE, RESTON, VA., MARCH 13–15, 1974
Grey, J.
New York, American Institute of Aeronautics and Astronautics, Inc., 1974. 43 p.

Technical aspects of aircraft fuel conservation are reviewed and discussed, and measures to be taken having the

best prospects for short-term and long-term impact are recommended. Fuel conservation is discussed from the viewpoint of aircraft operations, design, propulsion systems, and fuels. Some of the principal measures identified included increasing load factors, achieved by revised rerouting and scheduling and routing patterns, matching aircraft size to demand, and better matching of total service to the market; research on advanced onboard avionics which will give the pilot sufficient information for him to make real-time selection of fuel-optimum flight profiles and airspeeds; drag reduction by the use of a properly designed small vertical 'winglet' located just inboard of each wingtip; the implementation of supercritical aerodynamic wing designs; increase in frequency and tightening the standards of regular engine maintenance procedures; and modification of hydrocarbon fuels currently used by relaxation of freeze point and flash point specifications and by use of wider fractions and more aromatics. ABA P.T.H.

NASA-CP-2033 E-9457 78/00/00 78N19325
JET AIRCRAFT HYDROCARBON FUELS TECHNOLOGY
Longwell, J.P.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. Workshop held at Cleveland, Ohio, 7–9 June 1977.

A broad specification, referee fuel was proposed for research and development. This fuel has a lower, closely specified hydrogen content and higher final boiling point and freezing point than ASTM jet A. The workshop recommended various priority items for fuel research and development. Key items include prediction of tradeoffs among fuel refining, distribution, and aircraft operating costs; combustor liner temperature and emissions studies; and practical simulator investigations of the effect of high freezing point and low thermal stability fuels on aircraft fuel systems. ABA author.

NASA-TM-73884 77/00/00 78N17060
GENERAL AVIATION ENERGY-CONSERVATION RESEARCH PROGRAMS AT NASA-LEWIS RESEARCH CENTER
Willis, E.A.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. Presented at the Conf. on Energy Conserv. in Gen. Aviation, Kalamazoo, Mich., 10–11 Oct. 1977; sponsored by Western Michigan Univ.

The major thrust of NASA's nonturbine general aviation engine programs is directed toward (1) reduced specific fuel consumption, (2) improved fuel tolerance; and (3) emission reduction. Current and planned future programs in such areas as lean operation, improved fuel management, advanced cooling techniques and advanced engine concepts, are described. These are expected to lay the technology base, by the mid to latter 1980's, for engines whose total fuel costs are as much as 30% lower than today's conventional engines. ABA author.

77/10/00 78N11074
ALTERNATIVE FUELS
Grobman, J.S.; Butze, H.F.; Friedman, R.; Antoine, A.C; Reynolds, T.W.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. In its Aircraft Eng. Emissions p.277-308 (see N78-11063 02-07)

Potential problems related to the use of alternative aviation turbine fuels are discussed and both ongoing and required research into these fuels is described. This discussion is limited to aviation turbine fuels composed of liquid hydrocarbons. The advantages and disadvantages of the various solutions to the problems are summarized. The first solution is to continue to develop the necessary technology at the refinery to produce specification jet fuels regardless of the crude source. The second solution is to minimize energy consumption at the refinery and keep fuel costs down by relaxing specifications. ABA author.

AD-A039597 R-1829-PR 76/12/00 77N30261
THE POTENTIAL ROLE OF TECHNOLGICAL MODIFICATIONS AND ALTERNATIVE FUELS IN ALLEVIATING AIR FORCE ENERGY PROBLEMS
Gebman, J.R.; Stanley, W.L.; Weyant, J.P.; Mikolowsky, W.T.
Rand Corp., Santa Monica, Calif.

This Report examines short- and long-term measures to reduce the consumption of petroleum jet fuels by the air force. Engine retrofits and aerodynamic modifications to existing aircraft can save significant quantities of jet fuel; however, savings in fuel expenditures are not enough to offset high initial costs of engine retrofits. If accomplished early in an aircraft's life cycle, relatively lower costs of modest aerodynamic modifications may be recoverable through savings in fuel expenditures. Synthetic JP fuels derived from oil shale or coal appear to be the most attractive future alternatives to petroleum jet fuels. If the foreign oil Cartel maintains its price-setting effectiveness and synthetic fuels industry develops in the United States, development of an air force capability to interchangeable use fuels derived from crude oil, oil shale, or coal could be economically attractive and enhance the air force's position in the jet fuel marketplace. ABA author (GRA).

NASA-CR-135136 R76AEG597 76/12/00 77N15043
STUDY OF UNCONVENTIONAL AIRCRAFT ENGINES DESIGNED FOR LOW ENERGY CONSUMPTION
Neitzel, R.E.; Hirschkron, R.; Johnston, R.P.
General Electric Co., Cincinnati, Ohio.
(Aircraft Engine Group.)

A study of unconventional engine cycle concepts, which may offer significantly lower energy consumption than conventional subsonic transport turbofans, is described herein. A number of unconventional engine concepts were identified and parametrically studied to determine their relative fuel-saving potential. Based on results from these studies, regenerative, geared, and variable-boost turbofans, and combinations thereof, were selected along with advanced turboprop cycles for further evaluation and refinement. Preliminary aerodynamic and mechanical designs of these unconventional engine configurations were conducted and mission performance was compared to a conventional, direct-drive turbofan reference engine. Consideration is given to the unconventional concepts, and their state of readiness for application. Areas of needed technology advancement are identified. ABA author.

NASA-CR-135053 R76AEG432 76/08/00 76N30218
STUDY OF TURBOFAN ENGINES DESIGNED FOR LOW ENERGY CONSUMPTION
Neitzel, R.E.; Hirschkron, R.; Johnston, R.P.
General Electric Co., Cincinnati, Ohio.
(Aircraft Engine Group.)

Subsonic transport turbofan engine design and technology features which have promise of improving aircraft energy consumption are described. Task I addressed the selection and evaluation of features for the CF6 family of engines in current aircraft, and growth models of these aircraft. Task II involved cycle studies and the evaluation of technology features for advanced technology turbofans, consistent with initial service in 1985. Task III pursued the refined analysis of a specific design of an advanced technology turbofan engine selected as the result of task II studies. In all of the above, the impact upon aircraft economics, as well as energy consumption, was evaluated. Task IV summarized recommendations for technology developments which would be necessary to achieve the improvements in energy consumption identified. ABA author.

NASA-CR-135065 PWA-5434 76/06/00 76N29233
STUDY OF UNCONVENTIONAL AIRCRAFT ENGINES DESIGNED FOR LOW ENERGY CONSUMPTION
Gray, D.E.
Pratt and Whitney Aircraft, East Hartford, Conn.

Declining US oil reserves and escalating energy costs underline the need for reducing fuel consumption in aircraft engines. The most promising unconventional aircraft engines based on their potential for fuel savings and improved economics are identified. The engines installed in both a long-range and medium-range aircraft were evaluated. Projected technology advances are identified and evaluated for their state-of-readiness for application to a commercial transport. Programs are recommended for developing the necessary technology. ABA author.

NASA-CR-134972 R76AEG268 76/01/00 76N22398
EXPERIMENTAL CLEAN COMBUSTOR PROGRAM, ALTERNATE FUELS ADDENDUM, PHASE 2
Gleason, C.C.; Bahr, D.W.
General Electric Co., Evendale, Ohio.

The characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader range combustion properties of petroleum or coal derived fuels were studied. Five fuels were evaluated; conventional JP-5, conventional No.2 diesel, two different blends of jet A and commercial aromatic mixtures – zylene bottoms and naphthalene charge stock, and a fuel derived from shale oil crude which was refined to jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a radial/axial staged combustor, and a double annular combustor. Performance and pollutant emissions characteristics at idle and simulated takeoff conditions were evaluated in a full annular combustor rig. Altitude relight characteristics were evaluated in a 60 degree sector combustor rig. Carboning and flashback characteristics at simulated takeoff conditions were evaluated in a 12 degree sector combustor rig. For the five fuels tested, effects were moderate, but well defined. ABA author.

NASA-CR135002 PWA-5318 76/04/00 76N22197
STUDY OF TURBOFAN ENGINES DESIGNED FOR LOW ENERGY CONSUMPTION
Gray, D.E.
Pratt and Whitney Aircraft, East Hartford, Conn.

The near-term technology improvements which can reduce the fuel consumed in the JT9D, JT8D, and JT3D turbofans in commercial fleet operation through the 1980's are identified. Projected technology advances are identified and evaluated for new turbofans to be developed after 1985. Programs are recommended for developing the necessary technology. ABA author.

75/00/00 75N31074
FUEL-CONSERVATIVE ENGINE TECHNOLOGY
Dugan, J.F., Jr; McAulay, J.E; Reynolds, T.W.; Strack, W.C.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. In its Aeron. Propulsion p.157-190 (see N75-31068 22-07).

Aircraft fuel consumption is discussed in terms of its efficient use, and the conversion of energy from sources other than petroleum. Topics discussed include fuel from coal and oil shale, hydrogen deficiency of alternate sources, alternate fuels evaluation program, and future engines. ABA F.O.S.

NASA-TM-X-71785 E-8450 75/08/00 75N30178
PRELIMINARY STUDY OF THE FUEL SAVING POTENTIAL OF REGENERATIVE TURBOFANS FOR COMMERCIAL SUBSONIC TRANSPORTS
Kraft, G.A.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.

The fuel savings potential of regenerative turbofans was calculated and compared with that of a reference turbofan. At the design altitude of 10.67 km and Mach 0.80, the turbine-inlet-temperature of the regenerative turbofan was fixed at 1700 K while the overall pressure ratio was varied from 10 to 20. The fan pressure ratio was fixed at 1.6 and the bypass ratio varied from 8 to 10. The heat exchanger design parameters such as pressure drop and effectiveness varied from 4 to 8 percent and from 0.80 to 0.90 respectively. Results indicate a fuel savings due to regeneration of 4.1 percent and no change in takeoff gross weight. ABA author.

75/00/00 75N29012
THE LONG TERM ENERGY PROBLEM AND AERONAUTICS
Rudey, R.A.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. In its NASA/Univ. Conf. on Aeron. p.183-210 (see N75-29001 20-01).

The projected increase in energy consumption by transportation in general and civil aviation in particular is directly opposed to the dwindling supplies of natural petroleum crude oil currently used to produce aircraft fuels. This fact dictates the need to develop even more energy conservative aircraft and propulsion systems than are currently available and to explore the potential of alternative fuels to replace the current petroleum derived hydrocarbons. Advances in technology are described in the areas of improved component efficiency, aircraft and engine integration, control systems, and advanced lightweight materials that are needed to maximize performance and minimize fuel usage. Also, improved turbofan and unconventional engine cycles which can provide significant fuel usage reductions are described. These advancements must be accomplished within expected environmental constraints such as noise and pollution limits. Alternative fuels derived from oil shale and coal are described, and the possible technological advancements needed to use these fuels in aircraft engines are discussed and evaluated with relation to potential differences in fuel characteristics. ABA author.

NASA-TM-X-71740 E-8371 75/05/00 75N24739
PRELIMINARY STUDY OF ADVANCED TURBOPROPS FOR LOW ENERGY CONSUMPTION
Kraft, G.A.; Strack, W.C.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.

The fuel savings potential of advanced turboprops (operational about 1985) was calculated and compared with that of an advanced turbofan for use in an advanced subsonic transport. At the design point, altitude 10.67 km and Mach 0.80, turbine-inlet temperature was fixed at 1590 K while overall pressure ratio was varied from 25 to 50. The regenerative turboprop had a pressure ratio of only 10 and an 85 percent effective rotary heat exchanger. Variable camber propellers were used with an efficiency of 85 percent. The study indicated a fuel savings of 33 percent, a takeoff gross weight reduction of 15 percent, and a direct operating cost reduction of 18 percent was possible when turboprops were used instead of the reference turbofan at a range of 10 to 200 km. These reductions were 28, 11, and 14 percent, respectively, at a range of 5500 km increasing overall pressure ratio from 25 to 50 saved little fuel and slightly increased takeoff gross weight. ABA author.

NASA-TM-X-71663 E-8241 75/02/00 75N18241
PRELIMINARY STUDY OF ADVANCED TURBOFANS FOR LOW ENERGY CONSUMPTION
Knip, G.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.

This analysis determines the effect of higher overall engine pressure ratios (OPR's), bypass ratios (BPR's), and turbine rotor-inlet temperature on a Mach 0.85 transport having a range of 5556 km (3000 nmi) and carrying a payload of 18144 kg (40,000 lbs – 200 passengers). Sideline noises (jet plus fan) of between 91 and 106 EPNdB (FAR 36) are considered. Takeoff gross weight (TOGW), fuel consumption (kg/pass. km) and direct operating cost (DOC) are used at the figures of merit. Based on predicted 1985 levels of engine technology and a noise goal of 96 EPNdB. The higher-OPR engine results in an airplane that is 18 percent lighter in terms of TOGW, uses 22.3 percent less fuel, and has a 14.7 percent lower DOC than a comparable airplane powered by a current turbofan. Cooling the compressor bleed air and lowering the cruise Mach number appear attractive in terms of further improving the figures of merit. ABA author.

AD-763097 AFAPL-TR-72-103 73/05/00 73N29804
HYDROGEN CONTENT AS A MEASURE OF THE COMBUSTION PERFORMANCE OF HYDROCARBON FUELS
Martel, C.R; Angello, L.C.
Air Force Aero Propulsion Lab., Wright-Patterson AFB, Ohio.

Previous work by various investigators has shown that the hyd.ogen content of a hydrocarbon jet fuel is the primary variable affecting the combustion performance of the fuel; i.e. the amount of heat radiated during the combustion of the fuel within the jet engine combustor. The results of statistical correlations of fuel data are presented wherein the hydrogen content of fuels is correlated with other fuel combustion measurements including smoke point, luminometer number, and net heat of combustion. Also, the hydrogen content of fuel is correlated with the specific gravity and aniline point measurements. The report concludes that the fuels' hydrogen content can be calculated with sufficient accuracy to eliminate the need for measuring smoke points, luminometer numbers, and net heat of combustion. For conventional jet fuels (JP-4, JP-5, JP-8, jet A, jet A-1, and jet-B) a minimum allowable hydrogen content of 13.5% by weight is recommended. ABA author (GRA).

CATEGORY 2 – ENERGY CONSERVATION IN AIRCRAFT DESIGN

76/08/00   76A39843
CONCEPTUAL DESIGN OF REDUCED ENERGY TRANSPORTS
Ardema, M.D.; Harper, M.; Smith, C.L.; Waters, M.H.; Williams, L.J.
(NASA, Ames Research Center, Moffett Field, Calif.)
National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. Journal of Aircraft, Vol.13, Aug. 1976, p.545-550.

The paper reports the results of a conceptual design study of new near-term fuel conservative aircraft. A parametric study was made to determine the effects of cruise Mach number and fuel cost on the optimum configuration characteristics and relative economic performance. Supercritical wing technology and advanced engine cycles were assumed. For each design, the wing geometry was selected to maximize an economic figure of merit which reflects the potential rate of return on investment. Based on the results of the parametric study, a reduced energy configuration was selected. Compared with existing transport design, the reduced energy design has a higher aspect ratio wing with lower sweep. and cruises at a slightly lower Mach number. It yields about 30% more seat-miles/gal than current wide body aircraft. At the higher fuel costs anticipated in the future, the reduced energy design has about the same economic performance as existing designs with the same technology level. As an example of a far-term technology application, a design with a composite material wing was also investigated. ABA author.

75/00/00   76A10391
THE 1974 ENERGY CRISIS – A PERSPECTIVE – THE EFFECT ON COMMERCIAL AIRCRAFT DESIGN
Steiner, J.E.
(Boeing Commercial Airplane Co., Renton, Wash.)
In International Air Transportation; Proceedings of the Conference, San Francisco, Calif., March 24–26, 1975. (A76-10389 01-03) San Francisco, American Society of Civil Engineers, 1975, p.19-31.

The paper identifies some aspects of aircraft design which have been and will be strongly affected by the design criterion of minimum fuel usage necessitated by the increased fuel costs in airline operation. Nonfan aircraft have either been retired or refurbished. Reduction of cruise speed yielded much greater savings on fuel than the increase in such items as crew pay account. Rescheduling was done to achieve higher load factors. Development of simple refan and high-bypass engines is necessary, but will also entail redesign of airfoil and airframe for optimal performance. Higher aspect ratio wing and cruise speed optimization will provide lower trip fuel, reduced engine size, and increased fuel volume. More accurate flying will result in fuel savings, which will hinge on automation in ATC and advanced navigation capability in aircraft. ABA P.T.H.

SAWE Paper 1091   75/05/00   75A47509
WEIGHT CONTRIBUTION TO FUEL CONSERVATION FOR TERMINAL AREA COMPATIBLE AIRCRAFT
Hanks, G.W.
(Boeing Co., Seattle, Wash.)
Society of Allied Weight Engineers, Annual Conference, 34th, Seattle, Wash., May 5–7, 1975, 25 p.

The contribution to reductions in fuel consumption by potential weight characteristics of advanced aircraft are considered, and trades between weight reduction versus increased aerodynamic and operating efficiency are discussed. Direct reductions in fuel use may be obtained by application of advanced technology in structure and airfoils, proper engine choice, and revised environmental control features. Weight penalties involved in wing planform optimization are countered by increased aerodynamic efficiency. Results of studies of an M = 0.80, 200 passenger, 5556 km design incorporating advanced structure, airfoils, and propulsion show 21.6% reductions in operational empty weight and take-off gross weight as compared to a conventional design. Features for reduction of congestion and emissions offer fuel reduction potential; noise reduction devices carry weight and fuel-use penalties. Implementation of the described fuel reduction approaches will yield an estimated 25% reduction in fuel consumption. ABA C.K.D.

AIAA Paper 75-1036   75/08/00   75A41698
FUEL CONSERVATION POSSIBILITIES FOR TERMINAL AREA COMPATIBLE TRANSPORT AIRCRAFT
Hanks, G.W.; Heath, A.R., Jr
(Boeing Commercial Airplane Co., Seattle, Wash.); (NASA, Langley Research Center, Hampton, Va.)
American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting, Los Angeles, Calif., Aug. 4–7, 1975, 14 p.

Design characteristics that would reduce mission fuel consumption and improve terminal-area operations for advanced transports are discussed. Sensitivity studies of the effects of cruise speed, wing geometry, propulsion cycle, operational procedures, and payload on fuel usage are presented and utilized to arrive at a conceptual configuration which offers [illegible] fuel savings as well as desirable operational characteristics in the terminal area. Technical and economic evaluation is provided in the form of a comparison of the resulting configuration with transports reflecting the current level of technology. The research and technology programs require to realize potential benefits are described. ABA (author).

SAE Paper 750587 75/05/00 75A40502
DESIGN OF SHORT HAUL AIRCRAFT FOR FUEL CONSERVATION
Bowden, M.K.; Sweet, H.S.; Waters, M.H.
(Lockheed-Georgia Co., Marietta, Ga.); (NASA, Ames Research Center, Moffett Field, Calif.)
Society of Automotive Engineers, Air Transportation Meeting, Hartford, Conn., May 6–8, 1975, 16 p.

Current jet fuel prices of twice the 1972 level have significantly changed the characteristics of airplane design for best economy. The results of a contract with the NASA Ames advanced concepts and missions division confirmed the economic desirability of lower design cruise speeds and higher aspect-ratio wings compared to designs developed in the by-gone era of low fuel price. Evauation of potential fuel conservation for short-haul aircraft showed that an interaction of airfoil technology and desirable engine characteristics is important: the supercritical airfoil permits higher aspect ratio wings with lower sweep; these, in turn, lower the cruise thrust requirements so that engines with higher bypass ratios are better matched in terms of lapse rate; lower cruise speeds (which are also better for fuel and operating cost economy) push the desired bypass ratio up further. Thus, if fuel prices remain high, or rise further, striking reductions in community noise level can be achieved as a fallout in development of a 1980s airplane and engine. Analyses are presented of developmental trends in the design of short-haul aircraft with lower cruise speeds and higher aspect-ratio wings, and the effects on fuel consumption of design field length, powered lift concepts, and turboprop as well as turbofan propulsion are discussed. ABA (author).

74/12/00 75A14346
RATING AIRCRAFT ON ENERGY
Maddalon, D.V.
(NASA, Langley Research Center, Aeronautical Systems Div., Hampton, Va.)
Astronautics and Aeronautics, Vol.12, Dec. 1974, p.26-43.

Questions concerning the energy efficiency of aircraft compared to ground transport are considered, taking into account as energy intensity the energy consumed per passenger statute mile. It is found that today's transport aircraft have an energy intensity potential comparable to that of ground modes. Possibilities for improving the energy density are also much better in the case of aircraft than in the case of ground transporation. Approaches for potential reductions in aircraft energy consumption are examined, giving attention to steps for increasing the efficiency of present aircraft and to reductions in energy intensity obtainable by the introduction of new aircraft utilizing an advanced technology. The use of supercritical aerodynamics is discussed along with the employment of composite structures, advances in propulsion systems, and the introduction of very large aircraft. Other improvements in fuel economy can be obtained by a reduction of skin-friction drag and a use of hydrogen fuel. ABA G.R.

74/00/00 74[illegible]316
A REVIEW OF PRECIOUS RESOURCES AND THEIR EFFECT ON AIR TRANSPORT; PROCEEDINGS OF THE SPRING CONVENTION, LONDON, ENGLAND, MAY 15, 16, 1974
Convention Sponsored by the Royal Aeronautical Society. London, Royal Aeronautical Society, 1974. 282 p.

Papers on air transport resources are given, covering nuclear contribution to future energy supplies, alternative energy sources, metallic and other material resources, noise reduction goals, effects of fuel and materials shortages on aircraft development and operation, future propulsion technology for ground transport, and economic resources utilization in avaition. The pricing policies of oil producing nations, hydrogen energy systems, man as a precious resource, and the quality of life vs aeronautics are also dealt with. Individual items are announced in this issue. ABA V.Z.

AD-A023765 76/04/00 78N72419
REPORT TO CONGRESS BY THE FEDERAL AVIATION ADMINISTRATION ON PROPOSED PROGRAMS FOR AVIATION ENERGY SAVINGS: FEDERAL AVIATION ADMINISTRATION, WASHINGTON, D.C.

ORNL-NSF-EP-69 74/05/00 77N85921
AIRPLANE ENERGY USE AND CONSERVATION STRATEGIES
Pilati, D.A.
Oak Ridge National Lab., Tenn.

77/12/00 78N1840
AIR TRANSPORTATION ENERGY EFFICIENCY
Williams, L.J.
National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif. In Union Coll. Effects of Energy Constraints on Transportation Systems. p.215-239 (see N78-18529 09-44).

The energy efficiency of air transportation, results of the recently completed RECAT studies on improvement alternatives, and the NASA aircraft energy efficiency research program to develop the technology for significant improvements in future aircraft were reveiwed. ABA author.

PB-271249/5 CED-77-98 77/08/15 78N12552
EFFECTIVE FUEL CONSERVATION PROGRAMS COULD SAVE MILLIONS OF GALLONS OF AVIATION FUEL: GENERAL ACCOUNTING OFFICE, WASHINGTON, D.C.
(Community and Economic Development Div.)

Federal actions to conserve fuel used by the airlines are discussed and additional fuel saving methods are suggested. ABA GRA.

AGARD-R-654 ISBN 92-835-1247-2 77/06/00 77N32091
SPECIAL COURSE ON CONCEPTS FOR DRAG REDUCTION: ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT, PARIS (FRANCE).
Presented at an AGARD Special Course at the Von Kármán Inst., Rhode-St-Genese, Belgium, 28 Mar. – 1 Apr. 1977.

NASA-CR-137924 MDC-J7340-Vol-2 76/06/00 77N23073
COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM. VOLUME 2: MARKET AND ECONOMIC ANALYSES.
Vanabkoude, J.C.
Douglas Aircraft Co., Inc., Long Beach, Calif.

The impact of the most promising fuel conserving options on fuel consumption, passenger demand, operating costs, and airline profits when implemented into the US domestic and international airline fleets is assessed. The potential fuel savings achievable in the US scheduled air transportation system over the forecast period, 1973 – 1990, are estimated. ABA author.

NASA-CR-137923 MDC-J7340-Vol-1 76/06/00 77N23072
COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM. VOLUME 1: TECHNICAL ANALYSIS
Kraus, E.F
Douglas Aircraft Co., Inc., Long Beach, Calif.

The effectiveness and associated costs of operational and technical options for reduced fuel consumption by Douglas Aircraft in the domestic airline fleet are assessed. Areas explored include alternative procedures for airline and flight operations, advanced and state of the art technology, modification and derivative configurations, new near-term aircraft, turboprop configuration studies, and optimum aircraft geometry. Data for each aircraft studied is presented in tables and graphs. ABA A.R.H.

GPO-78-544 76/00/00 77N15212
ALTERNATIVE FUELS FOR AVIATION: COMMITTEE ON AERONAUTICAL AND SPACE SCIENCES (US SENATE).
Hearing before Subcomm. on Aerospace Technol. and Natl. needs of Comm. on Aeronaut. and Space Sci., 94th Congr., 2D Sess., 27 – 28 Sep. 1976.

Research and progress in the development of alternative fuels for aviation are discussed. The impact of using non-optimum synthetic hydrocarbon based fuels on aeronautical structures and the cost of commercial airfares is explored. ABA A.H.

NASA-CR-137927 LR-27769-1 76/08/00 77N15008
STUDY OF THE COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM
Hopkins, J.P.; Wharton, H.E.
Lockheed-California Co., Burbank.

For abstract, see preceding accession.

AD-A023527 TASC-TR-545-1 AFFDL-TR-75-156 76/02/00 76N32333
ENERGY MANAGEMENT TECHNIQUES FOR FUEL CONSERVATION IN MILITARY TRANSPORT AIRCRAFT
Stengel, R.F.; Marcus, F.J.
Analytic Sciences Corp., Reading, Mass.

This report presents the results of an investigation of energy management techniques for fuel conservation in a large transport aircraft, the USAF C-141A. Using the methods of optimal control theory and numerical simulation, fuel-optimal flight paths are computed and compared with conventional vertical profiles for typical mission scenarios. Algorithms for on-board guidance to minimize fuel use are synthesized and evaluated, and functional requirements for system implementation are developed. Concepts for flight testing this throttle/energy management technique are presented. ABA GRA.

NASA-CR-137891 76/06/00 76N31079
STUDY OF COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM
Coykendall, R.E.; Curry, J.K.; Domke, A.E.; Madsen, S.E.
United Air Lines, Inc., San Francisco, Calif.

Economic studies were conducted for three general fuel conserving options (1) improving fuel consumption characteristics of existing aircraft via retrofit modifications; (2) introducing fuel efficient derivations of existing production aircraft and/or introducing fuel efficient, current state-of-the-art new aircraft; and (3) introducing an advanced state-of-the-art turboprop airplane. These studies were designed to produce an optimum airline fleet mix for the years 1980, 1985 and 1990. The fleet selected accommodated a normal growth market by introducing somewhat larger aircraft while solving for maximum departure frequencies and a minimum load factor corresponding to a 15% investment hurdle rate. Fuel burnt per available-seat-mile flown would drop 22% from 1980 to 1990 due to the use of more fuel efficient aircraft designs, larger average aircraft size, and increased seating density. An inflight survey was taken to determine air traveler attitudes towards a new generation of advanced turboprops. ABA author.

NASA-TM-X-73922 76/07/00 76N28224
STUDY OF OPERATIONAL PARAMETERS IMPACTING HELICOPTER FUEL CONSUMPTION
Cross, J.L.; Stevens, D.D.
National Aeronautics and Space Administration. Langley Research Center, Langley Station, Va.

A computerized study of operational parameters affecting helicopter fuel consumption was conducted as an integral part of the NASA civil helicopter technology program. The study utilized the helicopter sizing and performance computer program (HESCOMP) developed by the Boeing-VERTOL company and NASA Ames Research Center. An introduction to HESCOMP is incorporated in this report. The results presented were calculated using the NASA CH-53 civil helicopter research aircraft specifications. Plots from which optimum flight conditions for minimum fuel use that can be obtained are presented for this aircraft. The results of the study are considered to be generally indicative of trends for all helicopters. ABA author.

NASA-CR-137878 UTRC-R-76-912036-17 76/06/00 76N28204
COST/BENEFIT TRADE-OFFS FOR REDUCING THE ENERGY CONSUMPTION OF COMMERCIAL AIR TRANSPORTATION (RECAT)
Gobetz, F.W.; Leshane, A.A.
United Technologies Research Center, East Hartford, Conn.

The RECAT study evaluated the opportunities for reducing the energy requirements of the US domestic air passenger transport system through improved operational techniques, modified in-service aircraft, derivatives of current production models, or new aircraft using either current or advanced technology. Each of these fuel-conserving alternatives was investigated individually to test its potential for fuel conservation relative to a hypothetical baseline case in which current, in-production aircraft types are assumed to operate, without modification and with current operational techniques, into the future out to the year 2000. Consequently, while the RECAT results lend insight into the directions in which technology can best be pursued for improved air transport fuel economy, no single option studied in the RECAT program is indicative of a realistic future scenario. ABA author.

NASA-CR-144949 LG76ER0076-Vol-2 76/05/00 76N24145
STUDY OF THE APPLICATION OF ADVANCED TECHNOLOGIES TO LAMINAR-FLOW CONTROL SYSTEMS FOR SUBSONIC TRANSPORTS. VOLUME 2: ANALYSES
Sturgeon, R.F.; Bennett, J.A.; Etchberger, F.R.; Ferrill, R.S.; Meade, L.E.
Lockheed-Georgia Co., Marietta.

For abstract, see N76-24144.

NASA-CR-144975 LG76ER0076-Vol-1 76/05/00 76N24144
STUDY OF THE APPLICATION OF ADVANCED TECHNOLOGIES TO LAMINAR FLOW CONTROL SYSTEMS FOR SUBSONIC TRANSPORTS. VOLUME 1: SUMMARY
Sturgeon, R.F.; Bennett, J.A.; Etchberger, F.R.; Ferrill, R.S.; Meade, L.E.
Lockheed-Georgia Co., Marietta.

A study was conducted to evaluate the technical and economic feasibility of applying laminar flow control to the wings and empennage of long-range subsonic transport aircraft compatible with initial operation in 1985. For a design mission range of 10,186 km (5500 n mi), advanced technology laminar-flow-control (LFC) and turbulent-flow (TF) aircraft were developed for both 200 and 400-passenger payloads, and compared on the basis of production costs, direct operating costs, and fuel efficiency. Parametric analyses were conducted to establish the optimum geometry for LFC and TF aircraft, advanced LFC system concepts and arrangements were evaluated, and configuration variations maximizing the effectiveness of LFC were developed. For the final LFC aircraft, analyses were conduncted to define maintenance costs and procedures, manufacturing costs and procedures, and operational considerations peculiar to LFC aircraft. Compared to the corresponding advanced technology TF transports, the 200- and 400-passenger LFC aircraft realized reductions in fuel consumption up to 28.2%, reductions in direct operating costs up to 8.4%, and improvements in fuel

efficiency, in ssm/lb of fuel, up to 39.4%. Compared to current commercial transports at the design range, the LFC study aircraft demonstrate improvements in fuel efficiency up to 131%. Research and technology requirements requisite to the development of the LFC transport aircraft were identified. ABA author.

NASA-CR-148148 REPT-75-163-1 75/10/06 76N23249
AN ASSESSMENT OF THE BENEFITS OF THE USE OF NASA DEVELOPED FUEL CONSERVATIVE TECHNOLOGY IN THE US COMMERCIAL AIRCRAFT FLEET
ECON, Inc., Princeton, N.J.

Cost and benefits of a fuel conservative aircraft technology program proposed by NASA are estimated. NASA defined six separate technology elements for the proposed program: (a) engine component improvement (b) composite structures (c) turboprops (d) laminar flow control (e) fuel conservative engine and (f) fuel conservative transport. There were two levels postulated: the baseline program was estimated to cost $490 million over 10 years with peak funding in 1980. The level two program was estimated to cost an additional $180 million also over 10 years. Discussions with NASA and with representatives of the major commercial airframe manufacturers were held to estimate the combinations of the technology elements most likely to be implemented, the potential fuel savings from each combination, and reasonable dates for incorporation of these new aircraft into the fleet. ABA author.

AD-A015927 AFOSR-75-1337TR 75/04/00 76N20886
PERIODIC CONTROL OF VEHICLE CRUISE: IMPROVED FUEL ECONOMY BY HIGH AND LOW FREQUENCY SWITCHING
Gilbert, E.G.
Michigan Univ., Ann Arbor. (Dept. of Aerospace Engineering)

It is shown that time-dependent periodic control can improve the fuel economy of vehicles in cruise. The time-dependent controls considered are relaxed steady-state (RSS) control, quasi-steady-state (QSS) control, and quasi-relaxed steady-state (QRSS) control. Examples are given which show that QRSS control may give better performance than either RSS or QSS control. Properties of optimal cost functions (dependent on the minimum required average speed) are derived. The possibility or impossibility of improved performance through the use of QRSS, QSS, and RSS control is investigated in terms of assumptions on the vehicle drag and fuel-consumption functions. ABA GRA.

PB-246271/1 FEA/B-75/588-Vol-1 75/06/00 76N18089
THE ECONOMIC IMPACT OF ENERGY SHORTAGES ON COMMERCIAL AIR TRANSPORTATION AND AVIATION MANUFACTURE. VOLUME 1: IMPACT ANALYSIS
Gorham, J.E.; Gross, D.; Snipes, J.C.
Stanford Research Inst., Arlington, Va.

The impact is evaluated of the energy shortage on commercial air transportation and its related manufacturing industries. As a result, the forces are analyzed of change at work in the air transportation industry relating to the energy crisis, both desirable and undesirable, that are likely to affect the way the industry does business, its efficiency or inefficiency in the use of fuel, the impact of continued fuel price increases, and the ability of the industry to use the most fuel-efficient aircraft presently or prospectively available. The cumulative impact is considered of these factors affecting air transportation on the need for, number of, and timing of requirements for new aircraft in order to assess the secondary impact on the aircraft, engines, and parts manufacturing industries. ABA GRA.

NASA-TM-X-71744 75/00/00 75N25298
CHALLENGE TO AVIATION: HATCHING A LEANER PTEROSAUER
Moss, F.E.
National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
Presented at Aeron. Propulsion Conf., Cleveland, 13 May 1975.

Modifications in commercial aircraft design, particularly the development of lighter aircraft, are discussed as effective means of reducing aviation fuel consumption. The modifications outlined include (1) use of the supercritical wing; (2) generation of the winglet; (3) production and flight testing of composite materials; and (4) implementation of fly-by-wire control systems. Attention is also given to engineering laminar air flow control, improving cargo payloads, and adapting hydrogen fuels for aircraft use. ABA L.B.

NASA-CR-132608 D6-22421 75/05/00 75N19224
FUEL CONSERVATION POSSIBILITIES FOR TERMINAL AREA COMPATIBLE AIRCRAFT
Boeing Commercial Airplane Co., Seattle, Wash.

Design features and operational procedures are identified, which would reduce fuel consumption of future transport aircraft. The fuel-saving potential can be realized during the last decade of this century only if the necessary research and technology programs are implemented in the areas of composite primary structure, airfoil/wing design, and stability augmentation systems. The necessary individual R and T programs are defined. The sensitivity to fuel usage of several design parameters (wing geometry, cruise speed, propulsion) is investigated, and the results applied to a candidate 18, 140-kg (40,000-lb) payload, 5556-km (3000-nmi) transport design. Technical and economic comparisons are made with current commercial aircraft and other advanced designs. ABA author.

NASA-TM-X-72659 75/02/00 75N17339
FUTURE LONG-RANGE TRANSPORTS: PROSPECTS FOR IMPROVED FUEL EFFICIENCY
Nagel, A.L.; Alford, W.J., Jr; Dugan, J.F., Jr
National Aeronautics and Space Administration. Langley Research Center, Langley Station, Va.

A status report is provided on current thinking concerning potential improvements in fuel efficiency and possible alternate fuels. Topics reviewed are: (1) historical trends in airplane efficiency; (2) technological opportunities including supercritical aerodynamics, (3) vortex diffusers, (4) composite materials, (5) propulsion systems, (6) active controls, and terminal-area operations; (7) unconventional design concepts, and (8) hydrogen-fueled airplane. ABA author.

74/12/00 75N16982
IMPACT ON AERODYNAMIC DESIGN
Hafer, X.
Technische Hochschule, Darmstadt (West Germany).
(Inst. für Flugtechnik.) In AGARD the 1974 AGARD Ann. Meeting. p.47-55 (see N75-16977 08-44).

The impact of fossil fuel consumption and anticipated shortages on aircraft design for improved efficiency is examined. Aerodynamic possibilities for improved efficiency are as follows: (1) aerodynamic configuration optimization, (2) boundary layer suction, (3) the oblique wing, and (4) supercritical airfoils. Aerodynamic improvements using active controls are as follows: (1) relaxed static stability, (2) maneuver load control, (3) active flutter control, and (4) gust alleviation and fatigue damage control. Changes in aircraft aerodynamics design resulting from the use of hydrogen fuel are analyzed. ABA author.

74/12/00 75N16979
ENERGY-RELATED RESEARCH AND DEVELOPMENT IN THE UNITED STATES AIR FORCE
Yarymovych, M.I.
Department of the Air Force, Washington, D.C. In AGARD the 1974 Ann. Meeting. p.21-30 (see N75-16977 08-44).

The requirements for petroleum based energy sources by the department of defense of the United States are analyzed. In addition to the requirements of the military forces, the logistic requirements are also examined. The impact of the energy crisis on military research and development programs to develop new energy sources for military use is examined. Methods of reducing fuel consumption by aircraft design and structural modification are proposed. The effectiveness of a campaign to reduce energy requirements and expenditures is documented. ABA author.

74/12/00 75N16977
THE 1974 AGARD ANNUAL MEETING: THE ENERGY PROBLEM – IMPACTS ON MILITARY RESEARCH AND DEVELOPMENT.
Advisory Group for Aerospace Research and Development, Paris (France).
Meeting held at Paris, 26 Sep. 1974.

NASA-CR-2502 75/02/00 75N16557
EVALUATION OF ADVANCED LIFT CONCEPTS AND POTENTIAL FUEL CONSERVATION FOR SHORT-HAUL AIRCRAFT
Sweet, H.S.; Renshaw, J.H.; Bowden, M.K.
Lockheed Aircraft Corp., Burbank, Calif.

The effect of different field lengths, cruise requirements, noise level, and engine cycle characteristics on minimizing fuel consumption and minimizing operating costs at high fuel prices were evaluated for some advanced short-haul aircraft. The conceptual aircraft were designed for 148 passengers using the upper surface-internally blown jet flap, the augmentor wing, and the mechanical flap lift systems. Advanced conceptual STOL engines were evaluated as well as a near-term turbofan and turboprop engine. Emphasis was given to designs meeting noise levels equivalent to 95-100 EPNdB at 152 m (500 ft) sideline. ABA author.

NASA-TM-X-71927 73/12/20 74N20654
AERONAUTICAL FUEL CONSERVATION POSSIBILITIES FOR ADVANCED SUBSONIC TRANSPORTS
Braslow, A.L.; Whitehead, A.H., Jr
National Aeronautics and Space Administration. Langley Research Center, Langley Station, Va.

The anticipated growth of air transportation is in danger of being constrained by increased prices and insecure sources of petroleum-based fuel. Fuel-conservation possibilities attainable through the application of advances in aeronautical technology to aircraft design are identified with the intent of stimulating NASA R and T and systems-study activities in the various disciplinary areas. The material includes drag reduction; weight reduction; increased efficiency of main and auxiliary power systems; unconventional air transport of cargo; and operational changes. ABA author.

R-1360-NSF 73/10/00 74N18606
THE POTENTIAL FOR ENERGY CONSERVATION IN COMMERCIAL AIR TRANSPORT
Mutch, J.J.
Rand Corp., Santa Monica, Calif.

The potential is examined for reducing the energy requirements of the US commercial airlines, with emphasis on the certificated-route air carriers. Measures stressed are independent of the level of traffic demand. They are intended to reduce energy requirements by decreasing the energy intensity of air transport. The possibility is examined of substituting more efficient transport modes for aviation in short-haul routes and the attendant net energy savings is assessed. Measures that yield benefits in both the short and long term are considered and their conservation potentials are quantified relative to present and future energy requirements. The results should be of interest to those involved in airline activities, including governmental regulatory and policymaking bodies, industry groups, and the airlines themselves. ABA author.

CATEGORY 3 – ENERGY RESOURCES FORECASTS

77/00/00 77A46093
ENERGY SUPPLY TO THE YEAR 2000: GLOBAL AND NATIONAL STUDIES
Martin, W.F.
Cambridge, Mass., MIT Press, 1977. 418 p.

The book reports the results of energy supply studies, conducted as an international project and involving over seventy-five people from fifteen countries. Methods were developed for estimating energy supply and demand through the year 2000 and for integrating them. A description is provided of the methodology and major conclusions of the supply studies. Individual global overviews are included for oil, natural gas, coal, nuclear energy, other fossil fuels, and renewables such as hydroelectricity and geothermal and solar energy. Individual national supply studies are discussed, giving attention to Canada, Denmark, Finland, France, The German Federal Republic, Italy, Japan, Mexico, The Netherlands, Norway, Sweden, The United Kingdom, and The United States. ABA G.R.

AD-A016433 SAI-74-630-WA RADC-TR-75-199 75/07/00 76N72630
ANALYSIS OF THE ENERGY RESOURCES AND DEMAND OF WESTERN EUROPE
Schneider, J.F.; Dance, K.D.; Lind, R.C.; Ryan, R.B.; Williams, A.R.
Science Applications, Inc., McLean, Va.

PB-255351/9 FEA/D-76/026 FEA/D-CP-48 76/07/00 77N10690
BASELINE ENERGY FORECASTS AND ANALYSIS OF ALTERNATIVE STRATEGIES FOR AIRLINE FUEL CONSERVATION
Urban Systems Research and Engineering, Inc., Cambridge, Mass.

Baseline forecasts of airline activity and energy consumption to 1990 were developed to evaluate the impact of fuel conservation strategies. Alternative policy options to reduce fuel consumption were identified and analyzed for three base line levels of aviation activity within the framework of an aviation activity/energy consumption model. By combining the identified policy options, a strategy was developed to provide incentives for airline fuel conservation. Strategies and policy options were evaluated in terms of their impact on airline fuel conservation and the functioning of the airline industry as well as the associated social environmental, and economic costs. ABA GRA.

AD-A022081 TETRAT-A-642-75-158 75/01/27 76N29736
SUMMARY OF NATO SYNTHETIC FUEL ALTERNATIVES
Tomlinson, G.
Tetra Tech, Inc., Arlington, Va.

In the past year, the problem of natural crude supply (and its cost) has reached critical proportions for the United States and Western Europe. In view of this crisis the NATO countries have been forced to consider such alternative fossil fuel sources as coal, oil shale, and tar sands for their military forces. The use of these fuels does not present a problem of supply, for the NATO nations have deposits of these fossil fuels that far exceed the proven world reserves of crude oil. It does, however, present a problem of technology – how to realize and use effectively the synthetic product of these deposits. Coal, for example, is particularly plentiful, exceeding the NATO oil reserves and oil shale and tar sands resources by almost a factor of ten. NATO Naval Forces are affected by the fuel shortage and cost since most NATO Naval ships and all its aircraft use liquid hydrocarbon fuels; the requirement for large quantities of liquid fossil fuels will continue for at least the next 25 years. Consequently, the military forces of NATO are particularly interested in the development of other sources and production methods for liquid fossil fuels. Conversion technologies for producing liquid fuel products from oil shale and coal have been demonstrated, a commercial tar sands plant is currently in operation in Canada, and several research and development programs are being conducted to improve the conversion process and to reduce the cost of synthetic fuels. The improved oil shale and coal conversion processes are now entering the pilot plant stage; commercial oil shale plants are expected to begin operation by 1980 and commercial coal liquefaction plants should begin operation by 1985. ABA GRA.

AD-A010712 CERL-TR-E-58 75/05/00 76N10562
PROJECTIONS OF ENERGY AVAILABILITY, COST, AND AGGREGATE DEMAND FOR 1975, 1980, 1985, 1990
Berstein, H.M.; Hinkle, B.K.; Bazques, E.O.
Hittman Associates, Inc., Columbia, Md.

This report investigates the availability, cost, and aggregate demand of energy resources for 1975, 1980, 1985, and 1990. The consumption of energy resources for 1970 has been included for comparative purposes. The energy sources examined include petroleum, gas, coal, nuclear, hydropower, solar, geothermal, and electricity. ABA GRA.

NASA-TM-X-62404 DOT-TST-74-13-1 74/06/00 75N13690
TRANSPORTATION VEHICLE ENERGY INTENSITIES. A JOINT DOT/NASA REFERENCE PAPER
Mascy, A.C.; Paullin, R.L.
(DOT, Washington)
National Aeronautics and Space Administration. Ames Research Center, Moffett Field, Calif.

A compilation of data on the energy consumption of air and ground vehicles is presented. The ratio BTU/ASM, British Thermal Units/Available Seat Mile, is used to express vehicle energy intensiveness, and related to the energy consumed directly in producing seat-mile or ton-mile productivity. Data is presented on passenger and freight vehicles which are in current use or which are about to enter service, and advanced vehicles which may be operational in the 1980's and beyond. For the advanced vehicles, an estimate is given of the date of initial operational service, and the performance characteristics. Other key considerations in interpreting energy intensiveness for a given mode are discussed, such as load factors, operations, overhead energy consumption, and energy investments in new structure and equipment. ABA author.

ORNL-NSF-EP-68 74/04/00 75N10039
TOTAL ENERGY USE FOR COMMERCIAL AVIATION IN THE US
Hirst, E.
Oak Ridge National Lab., Tenn.

The total energy impacts of commercial aviation in the United States are shown. Direct fuel use by commercial airplanes (1080 trillion BTU in 1971) amounts to 6% of direct fuel use for all domestic transportation, 1.6% of the total national energy budget. Indirect energy requirements are one-third as great as the direct fuel use. Thus, total energy demand for domestic commercial aviation in 1971 was 1450 trillion BTU, 2% of national energy use. Direct fuel savings due to adoption of airline conservation measures can be increased by one-third to account for the indirect energy savings. Some conservation measures, such as a reduction in short-haul flights, are likely to have larger energy savings, because short-haul flights involve higher maintenance costs, greater airport use, and higher passenger service costs on a passenger-mile basis than do longer flights. Other measures, such as reducing cruise speeds, are likely to have relatively small indirect energy savings. In all cases, the direct fuel savings can be increased by 20%. ABA NSA.

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14. Abstract

This AGARD Lecture Series No. 96 is sponsored by the Propulsion and Energetics Panel of AGARD and is implemented by the Consultant and Exchange Programme.

Future fuel supplies for aviation is an important matter. If the world continues to consume its petroleum resources at its current rate of consumption, it will essentially run out of these resources by the turn of the century. The need for aircraft fuel conservation is most urgent, if not mandatory, because the future of aviation as we know it today, is at stake. This lecture series is designed to provide various interested members of NATO with a better understanding of the problems facing the aerospace community and to provide an opportunity to review and assess what steps can and are being taken to alleviate this international problem.

Current and forecasted world energy demands, growth, and supply are reviewed in perspective to the status and outlook for future aviation fuels to meet NATO needs. The special problems associated with the refining of aviation fuels from lower quality feedstocks (including fuel refined from coal, oil shale, and tar sands) and techniques for reducing energy consumption in refining processes are examined. Special attention is given to the chemistry and combustion characteristics of future hydrocarbon fuels and the impact of using these fuels in aircraft engines and fuel systems. An assessment is made as to what technology advancements are currently underway and what other advancements are needed with reference to engine components, engine systems, aircraft designs and operational procedures to help conserve fuel resources.

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Propulsion and Energetics Panel and the Consultant and Exchange Programme of AGARD presented on 16-17 October, 1978 in Munich, Federal Republic of Germany, and 19-20 October, 1978 in London, UK. In addition, a one-day Round-Table Discussion was held in Paris, France on 13 October, 1978

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